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SUMMARY

A correlation study is made of some limited experimental film-boiling heat-transfer coefficients obtained from forced-flow boiling heat-transfer research with liquid hydrogen, nitrogen, and freon 113 as the working fluids. The data studied herein were all obtained with upward flow through electrically heated circular tubes.

Correlation is obtained by the development of a relation between a film-vaporization parameter and a function consisting of a ratio of an experimental Nusselt number modified by a two-phase correlation factor to a calculated turbulent vapor-phase Nusselt number. The film-vaporization parameter includes the heat flux measured downstream of the point along the tube at which transition from nucleate to film boiling is initiated (burnout location), the latent heat, and the fluid quality at the burnout location. The experimental Nusselt number is expressed in terms of the saturated vapor thermal conductivity. The film-boiling heat-transfer coefficient in this Nusselt number is given by the ratio of the local heating rate to the wall- to saturated-fluid-temperature difference. The experimental Nusselt number is modified by a two-phase correlation factor whose parameters include: vapor Reynolds number, heat-addition parameter, tube diameter and length, and several fluid-property parameters. All fluid properties are evaluated at the fluid saturation temperature (either local or average depending on the available data).

INTRODUCTION

The problem of forced-flow boiling heat transfer arises whenever the transfer of energy at high heat fluxes must be met, or when large amounts of vapor must be generated to drive turbomachinery. Because the governing equations for boiling heat transfer are not available at this time, it is not possible to optimize the design of a two-phase boiling system. The correlation of boiling heat-transfer data in the form of empirical dimensionless parameters, however, is of great usefulness for engineering applications.

The boiling phenomenon associated with vapor generation covers two primary heat-transfer regimes: nucleate boiling and film boiling. In nucleate boiling, large heat flux values can be achieved with accompanying small wall superheat values (tube wall- to fluid-saturation-temperature differences) with the result that large heat-transfer coefficients are obtained. In film boiling, the heat-transfer coefficient is significantly lower than that in the nucleate-boiling regime because large wall superheat values are obtained. Under some circumstances these large wall superheats can cause destructive failure or burnout of the component. The point of transition from nucleate to film boiling is frequently identified with a critical heat flux, and its location is often called the burnout point (ref. 1).

The film-boiling regime for two-phase turbulent forced flow with net vapor generation has been the subject of very few experimental studies. One paramount problem in the experimental studies has been the previously noted large, often excessive, values of wall temperature rise associated with film boiling. With the increased use of cryogenic fluids, research in the film-boiling regime has become more practical because these fluids, particularly hydrogen, permit film boiling to occur at wall temperatures considerably below the material failure temperature.

Reference 2 presents film-boiling data taken with liquid hydrogen. These data are correlated in terms of a Martinelli two-phase parameter $X_{tt,f}$ and a modified Dittus-Boelter equation for Nusselt number $Nu_{calc,f}$. (All symbols are defined in appendix A.) This correlation, together with the experimental data, is reproduced from reference 2 and shown in figure 1 herein. Examination of these data shows that, for any given run, significant trends exist with local tube length, heating rate, and mass velocity. (Note that tube length is measured downstream from the beginning of the heated portion of the test specimen; increasing axial length along the tube is indicated from right to left in fig. 1.) From these and other considerations, it appears that the Martinelli two-phase parameter, as used in reference 2, does not provide a satisfactory correlation of local film-boiling heat transfer in forced flow.

An apparent reduction in the spread of the data shown in figure 1 can be achieved over a limited range of conditions by multiplying the Nusselt number ratio shown in figure 1 by the product of the mass velocity and the latent heat divided by the heating rate, all modifying factors with an exponent of 0.4 (ref. 3). However, careful examination of the data indicates that this relation of these variables, although it is an important correlating parameter for film-boiling data, is not sufficient to eliminate all data trends. Consideration of data that extend the operating range significantly (ref. 1) shows further inadequacies in the correlation proposed in reference 3.

The present study was conducted at the NASA Lewis Research Center as part of a comprehensive program concerned with two-phase flow and heat-transfer phenomenon. Herein an empirical correlation of local film-boiling heat-transfer coefficients has been made for turbulent forced flow upward through electrically heated circular tubes (approximately uniform heat flux) with liquid hydrogen, nitrogen, and freon 113 as the working fluids. The correlation was obtained through trial-and-error solutions by the use of a film-vaporization parameter, which is plotted as a function of the ratio of experimental Nusselt number modified by a two-phase correlation factor to a calculated turbulent vapor-phase Nusselt number. The range of fluid pressures covered by the data used herein is shown in table I together with ranges of nominal values for the more important parameters used in the present correlation.

COMPUTATIONAL PROCEDURES

For the 0.313-inch inside diameter tube data of reference 2, local pressures along the tube were available that permitted the use of local fluid properties in the analysis. Such local pressures were not available for the 0.495-inch inside diameter tube data (ref. 2 and unpublished NASA data obtained during the same investigation). The analysis of these latter data was based on the fluid properties averaged for the tube inlet- and outlet-fluid-saturation temperatures and pressures. In reference 1, no measurable pressure drops across the test section were obtained, and the only pressure measurement reported was at the tube entrance. In reference 4 no pressure drop data were reported for the 0.408-inch diameter tube, while the small pressure drops reported for the 0.18-inch diameter tube were neglected in the present analysis.

The local heating rate q was essentially constant along the tube length for the data of reference 2 because of the tube material used; however, for the data of reference 1, the local heating rate was a function of the local wall temperature on account of the change in the electrical resistance of the tube material with temperature. The wall temperatures were obtained directly from the respective references. For data from reference 2, the inside tube wall temperature was reported. In reference 1, however, only the outer tube wall temperature was reported. These outer wall temperatures were not corrected herein because the temperature drop through the wall was considered negligible (generally less than 10° out of several hundred degrees to as high as 1800° F). In reference 4 only the average heating rates were reported; the authors stated that the local heating rates differed from the average values by less than ±7 percent. As in reference 1, outer wall temperatures given in reference 4 were not corrected herein because the temperature drop through the wall was considered negligible.

An examination of the data led to the elimination of points based on the following considerations that were considered to be influenced by tube-end effects:

(1) For the data of reference 1, the first temperature data point following the burnout location was discarded because the location of burnout could not be established well enough to avoid possible large errors in the initial l/D ratio when calculating the film-vaporization parameter. The last temperature data point at the tube exit was discarded because of obvious thermal end effects due to the presence of the electrical busses. The nearest valid temperature measurement to the tube exit was approximately 1.6 inches from the exit.

(2) The data selection used herein was the same as that used in reference 2; namely, the first temperature used in the analysis was obtained 0.625 inch from the tube entrance, and the farthest downstream on the tube was located about 1.6 inches from the tube exit. Thermocouples located closer than these limits to the tube entrances and exits were influenced by thermal end effects and consequently were in error.

(3) The first and last wall temperatures reported in reference 4 were not used in the present analysis because of possible thermal end effects; the initial wall temperature used in the present analysis was obtained $3\frac{1}{4}$ inches from the heated entrance of the tube, and the farthest downstream wall temperature used was located $3\frac{1}{4}$ inches from the tube exit.

The thermodynamic and the transport data used herein were compiled from several sources, some published (refs. 5 and 6) and some unpublished. Since there are insufficient saturation-property data for all cryogenic fluids, the author extrapolated the available data for his own use (see also ref. 2). The method used in this data extrapolation is discussed briefly in appendix B, and pertinent extrapolated fluid-property values used herein are shown in figure 2.

Ranges of the variables covered in the reference studies and used in the present study are shown in table I.

DEVELOPMENT OF CORRELATION PARAMETERS

In the empirical approach taken herein, a solution, achieved through trial-and-error means, for correlation of local heat-transfer coefficients in the film-boiling regime, was obtained through the development of (1) a film-vaporization parameter X_F and (2) a ratio of an experimental Nusselt number modified by a two-phase correlation factor to a calculated single-phase turbulent vapor Nusselt number.

Film-Vaporization Parameter

The film-vaporization parameter X_F is defined as

$$X_F = \frac{x_f}{1 - x_c} \tag{1}$$

where x_f for a fluid flowing through a circular tube is given by

$$x_f = \frac{4ql}{GDh_{fg}} \tag{2}$$

and x_c is the fluid quality at the burnout location. Values of x_c for the data of reference 1 were obtained from table II therein. For the data of references 2 and 4, the value of x_c was taken as zero for all runs; that is, the burnout location was assumed to coincide with the beginning of the heated portion of the test specimen. The length term l in equation (2) is the distance measured axially along the heated tube downstream from the burnout location. The present analysis is limited to constant or nearly constant heat flux with distance downstream of the burnout location. Average values of heat flux may be utilized only to obtain an approximate solution. The values of h_{fg} are those associated with the appropriate (local or average) saturation temperature.

When the burnout location coincides substantially with the heated tube entrance (data from ref. 2), x_c can be considered zero, and $X_F = x_f$. For this special case and with a constant heat flux along the tube, X_F is a measure of the thermodynamic fluid quality and, effectively, all vaporization of the fluid is assumed to occur in the film-boiling regime. When x_c has a significant value (ref. 1), X_F represents the vaporization in the film-boiling regime of only a portion of the total fluid flow and cannot be considered a quality term as in the previous case. In both cases, however, on the assumption that perfect thermal diffusion and mixing of the fluid occurs, the entire quantity of fluid passing through the heated tube is considered to be vaporized when X_F is 1.0.

Nusselt Number Considerations

Researchers frequently resort to the Nusselt number in attempting to correlate experimental heat-transfer coefficients. The Nusselt number for a circular tube and single-phase fluid is often written as

$$Nu = \frac{hD}{k} = \frac{qD}{(t_w - t_b)k} \tag{3}$$

and for the special case in which the fluid is at the saturation temperature

$$Nu = \frac{qD}{(t_w - t_s)k} \tag{4}$$

In both equations (3) and (4) only one fluid-property term is evident in the definitions of Nusselt number, namely, the thermal conductivity k of the fluid. The use of the liquid or the vapor thermal conductivity value for a single-phase fluid depends on the phase state of the fluid.

For two-phase flow, however, a more complex expression of thermal conductivity, depending on the fluid quality or the fluid void fraction, would have to be considered if two-phase property values are used as the basis for a correlation. In order to avoid this complexity, saturated vapor properties are arbitrarily used herein, and liquid properties are used only when necessary as modifying influences for data correlation.

For two-phase heat-transfer correlation purposes, it is often convenient to use a ratio of the experimental Nusselt number for two-phase flow to the calculated single-phase turbulent vapor Nusselt number as a significant parameter. A similar approach is used herein. The calculated single-phase vapor Nusselt number used in the present study, for which turbulent flow is assumed, is given by

$$Nu_{v,calc} = 0.023\ Re_v^{0.8} Pr_v^{0.4} \tag{5}$$

All property terms in equation (5) are based on the saturation conditions of the vapor phase, and the mass velocity in the Reynolds number is based on the total mass flow through the heated tube. The ratio of Nusselt numbers (eqs. (4) and (5)) can then be written as

$$\frac{Nu_{exp}}{Nu_{v,calc}} = \frac{h_{exp} \dfrac{D}{k_v}}{Nu_{v,calc}} = \frac{\left[\dfrac{qD}{(t_w - t_s)k_v}\right]_{exp}}{\left(0.023\ Re_v^{0.8} Pr_v^{0.4}\right)_{calc}} \tag{6}$$

The variation of the data in terms of equation (6) with the film-boiling vaporization parameter X_F is shown in figures 3 and 4 for hydrogen, nitrogen, and freon 113. It is quite evident from the wide spread in the data and the variation in the shapes of the data curves that equation (6) will not suffice to correlate the experimental data in terms of X_F. It had also been anticipated in setting up equation (6) that when X_F becomes 1.0 (and perfect mixing of the fluid phases is assumed), the ratio of Nusselt numbers expressed by equation (6) also becomes 1.0. On the other hand, it could also be reasoned from the data that, if perfect phase mixing did not occur, that is, if all the fluid had not vaporized when X_F is 1.0, the ratio of Nu_{exp}/Nu_{calc} would exceed 1.0 at $X_F = 1.0$. On the basis of heat-balance calculations, however, a significantly large portion of the data shows that the values of Nu_{exp}/Nu_{calc} are considerably less than 1.0 as X_F approaches 1.0 (all data from fig. 3 of ref. 2, and a significant amount of data from fig. 4 of refs. 1 and 4).

A number of runs from reference 2 with the 0.313-inch inside diameter tube show rapidly increasing values of Nu_{exp}/Nu_{calc} over the last one-third of the tube length (runs 18-2 to 20-1 in figs. 3(a) and (b)). These data are inconsistent with the other runs of the same investigation as well as those of reference 1. It should be noted that the same data points did not plot well for the correlation of reference 2 shown in figure 1.

Correlation Parameters

Examination of the data presented in figures 3 and 4 shows that the ratio of $Nu_{exp}/Nu_{v,calc}$ is a further function of the vapor Reynolds number Re_v, a heat-addition parameter Γ, the heated tube diameter, several fluid properties parameters, and the overall length L_e of the tube measured from the absolute entrance of the tube (not the heated portion) to the burnout location. Through a series of trial-and-error solutions, parameters were developed that correlated the data for each tube and finally for all the data in the three reference investigations.

The final equations developed for correlating local film-boiling heat-transfer coefficients are expressed as follows:

$$\frac{Nu_{exp}}{Nu_{v,calc}} F_{tp} = f(X_F) \tag{7}$$

where

$$F_{tp} = 2.0\times10^{-10}\alpha(\beta)^{0.167}(\gamma)^{\left[1.8-(X_F)^a\right]}(0.005)^{\left[1-(X_F)^a\right]}(N_B)^{-0.667} \tag{8}$$

and

$$\alpha = \left[4.2\left(1 - \frac{Re_v^2}{Re_v^2 + 5.85\times10^{11}}\right) + 0.92\right] \tag{9}$$

$$\beta = \left[\frac{g(\rho_l - \rho_v)D^2}{g_c\sigma_L}\right] \tag{10}$$

$$\gamma = \left[\frac{Re_v}{\Gamma}(\Gamma + 2500)\right] = \left[Re_v\left(1 + \frac{2500}{\Gamma}\right)\right] \tag{11}$$

$$\Gamma = \left(\frac{qD}{\mu_v h_{fg}}\right) \tag{12}$$

$$N_B = \frac{\mu_v^2\sqrt{g(\rho_l - \rho_v)}}{\rho_v(g_c\sigma_L)^{1.5}} \tag{13}$$

$$a = \left\{0.5\left[1 - \frac{(L_e/D)^2}{(L_e/D)^2 + 0.05}\right] + 0.13\right\} \tag{14}$$

For L_e/D values greater than 3.5, equation (14) can be assumed to have a constant value of 0.13, whereas for L_e/D values less than 3.5, equation (14) yields variable values for the exponent a. The term N_B is a fluid-property parameter developed in reference 7 and found useful in correlating other two-phase heat-transfer data. For convenience, a plot of N_B (taken from ref. 7) as a function of the ratio P_s/P_{cr} is shown in figure 5 for liquid hydrogen, nitrogen, and freon 113. The constant 2.0×10^{-10} in equation (8) was selected, in part, so that when X_F is 1.0, the value of $(Nu_{exp}/Nu_{v,calc})F_{tp}$ is also 1.0. Furthermore, the term $(0.005)^{\left[1-(X_F)^a\right]}$ in equation (8) was included to provide a nearly linear curve in the final correlation.

The data of references 1, 2, and 4 are plotted in terms of equation (7) in figure 6. In general, good agreement of the data is obtained for all fluids, although several hydrogen runs are significantly higher or lower than the average curve drawn through all the data. No explanation is offered at this time for these random departures from the average curve, but it should be noted that in the case of run 14-8 (fig. 6(b)) the heat-transfer coefficients given in reference 2 decrease with increasing tube length, whereas for all the other runs shown the coefficient generally increases with increasing tube length.

In figure 6(h) data from runs 26 and 27, having the lowest values of Γ used in the reference studies, lie above the general correlation curve. This occurrence may be due to the mathematical expression used for equation (11). It is possible that a change in flow model or pattern occurs at very low values of Γ (less than about 300), which is not considered by the form of equation (11). Consideration of such a flow-model change can be included in the correlation by changing equation (11) to the following:

$$\gamma = \left[\frac{Re_v}{0.95\left(\frac{\Gamma}{\Gamma + 1600}\right)^{1.5} + 0.05}\right] \tag{15}$$

However, it should be noted that, while the conditions for runs 26 and 27 are nearly identical, the data deviate by up to 30 percent. Additional data appear to be required in order to establish whether equation (11) or (15) should be used for low values of Γ. For values of Γ greater than 300, the results given by these two equations differ by less than 2 percent.

In the case of figure 6(g), the data shown are based on only one "valid" data point for each run; however, even these data are generally in reasonable agreement with the average curve. An explanation for the data being somewhat above the average curve is that these data points are still influenced by the accuracy and the judgment used in the establishment of the burnout location (ref. 1), which affects the calculation of the X_F value.

The correlation could be somewhat simplified if the exponent a (eq. (14)) had a constant value of 0.13, rather than being dependent on L_e/D for ratios of this term less than 3.5. Data for which L_e/D is approximately 0.9 and exponent a is 0.13 are presented in figure 7 together with the faired curve for all the data used herein. Similar results were obtained with the 0.18-inch diameter tube data of reference 4 ($L_e/D \cong 0.7$). It is apparent that with an exponent $a = 0.13$ these data plot with a reduced slope compared with the faired curve. Use of a variable exponent dependent on L_e/D (eq. (14)) yields a single-curve correlation that is applicable for all data used herein ($L_e/D > 0.7$) as shown previously in figure 6. Doubtful correlation of the data can be expected for L_e/D ratios in the range of 0 to 0.7 because exponent a is strongly influenced by the form of equation (14). Consequently, equation (14) should not be used in this range until data are available to establish the value of exponent a as L_e/D approaches zero.

A simplified solution for the film-boiling heat-transfer coefficient in the range of X_F from 0.01 to 1.0 can be made by the approximation of a straight-line variation (log-log plot) with a negative 45° slope for $(Nu_{exp}/Nu_{v,calc})F_{tp}$ against X_F in figure 6. This assumption leads to

$$\left(\frac{Nu_{exp}}{Nu_{v,calc}}\right)\left(F_{tp}\right) = \frac{1}{X_F} \tag{16}$$

and

$$h_{exp} = \frac{q}{(t_w - t_s)} = \left(\frac{Nu_{v,calc}}{X_F F_{tp}}\right)\left(\frac{k_v}{D}\right) \tag{17}$$

Equation (17) yields h_{exp} values within ±10 percent of those obtained from the curve shown in figure 6.

CONCLUDING REMARKS

The correlation of film-boiling heat-transfer coefficients developed herein should be applied only to the fluids included herein and in the general range of the variables listed in table I because of the limited data available for the analysis. It is important to note, however, that the freon 113 data obtained with the 0.408-inch diameter tube (ref. 4) were not used to establish the correlating parameters. These data, therefore, constitute an independent check on the development of these parameters, and hence on the apparent validity of the correlation. In the absence of specific data, it is not known whether further fluid-property and/or tube-geometry effects must be included if the correlation is extended to other fluids and channel geometries. For example, from the available data it cannot be determined whether a Prandtl number term, either liquid or vapor, should be included in the two-phase correlation factor F_{tp}. The Prandtl numbers for hydrogen, nitrogen, and freon 113 are too similar in magnitude to permit establishment of a dependency on this parameter. While such a factor may not be necessary for a fluid such as water (liquid and vapor Prandtl number ranges of the same order of magnitude as the liquids studied), it may well be necessary to include this parameter when liquid metals, with liquid Prandtl numbers some two orders of magnitude less than those for cryogenic fluids, are included in the correlation.

Thus, additional fluids and tube geometries should be studied experimentally and a wider range of operating conditions investigated in order to verify and extend the empirical relations developed herein.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 22, 1964

APPENDIX A

SYMBOLS

c_p	fluid specific heat, Btu/lb-mass, $^{\circ}R$
D	tube diameter (I.D.), ft
F_{tp}	two-phase modification factor (defined by eq. (8)), dimensionless
G	mass velocity, lb-mass/(hr)(sq ft)
g	acceleration (gravity), 4.17×10^8 ft/hr^2
g_c	conversion constant, 4.17×10^8, $\left(\frac{\text{lb-mass}}{\text{lb-force}}\right)\left(\frac{\text{ft}}{\text{hr}^2}\right)$
h	heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)
h_{fg}	latent heat of vaporization, Btu/lb-mass
k	thermal conductivity of fluid, Btu/(hr)(ft)($^{\circ}$R)
L	critical length measured from beginning of heated portion of tube to burnout location, ft or in.
L_e	sum of distance L and unheated upstream hydrodynamic portion of tube, ft
l	length along heated tube measured from burnout location, ft
N_B	boiling number (fluid-property parameter), $\frac{\mu_v^2\sqrt{g(\rho_l - \rho_v)}}{\rho_v(g_c\sigma_L)^{1.5}}$
Nu	Nusselt number, hD/k, dimensionless
$Nu_{calc,f}$	calculated Nusselt number based on film properties (ref. 2), dimensionless
$Nu_{v,calc}$	calculated vapor-phase Nusselt number, $0.023\ Re_v^{0.8}Pr_v^{0.4}$, dimensionless
P_{cr}	thermodynamic critical pressure for fluid, $\frac{\text{lb}}{\text{sq in.}}$ abs
P_s	saturation pressure, $\frac{\text{lb}}{\text{sq in.}}$ abs
Pr	Prandtl number, $c_p\mu/k$, dimensionless

Q	total heat input from burnout location to downstream location l (fig. 1), Btu/sec
q	heat flux, Btu/(hr)(sq ft)
Re	Reynolds number, GD/μ, dimensionless
t	temperature, $^{\circ}F$
W	mass flow rate of fluid, lb-mass/hr or lb-mass/sec (fig. 1 only)
X_F	film-boiling vaporization parameter, $x_f/(1 - x_c)$, dimensionless
x_c	thermodynamic fluid quality at burnout location, dimensionless
x_f	effective film-quality parameter in film-boiling regime, $4ql/DGh_{fg}$, dimensionless
$\alpha,\beta,\gamma,\Gamma$	film-boiling correlation parameters (defined by eqs. (9) to (12), respectively), dimensionless
μ	fluid viscosity, lb-mass/(hr)(ft)
ρ	fluid density, lb-mass/cu ft
σ_L	fluid surface tension, lb-force/ft
$\chi_{tt,f}$	Martinelli two-phase parameter (ref. 2), dimensionless

Subscripts:

b	bulk
cr	properties at the critical pressure point
exp	experimental
f	film conditions, arithmetic mean between wall and bulk temperature (ref. 2)
l	liquid
s	saturation temperature of fluid
v	vapor
w	wall

APPENDIX B

ESTIMATION OF SATURATED VAPOR PROPERTIES

FOR HYDROGEN AND NITROGEN

Examination of limited nitrogen and oxygen saturated vapor properties indicated that, in the range of interest for the data used herein, the ratio of $\mu_{v,s}/\mu_{cr}$ and $k_{v,s}/k_{cr}$ for these two fluids could be normalized on a single curve when plotted as a function of P_s/P_{cr}. Such plots are shown in figure 2(a). Similar data for hydrogen and freon 113 are not available. Saturated vapor properties for these two fluids were obtained by interpolation and extrapolation of established property values at 1 atmosphere, and the assumption that the variation of the ratios $\mu_{v,s}/\mu_{cr}$ and $k_{v,s}/k_{cr}$ as functions of P_s/P_{cr} for nitrogen and oxygen also apply.

Figure 2(b) shows the variation of $\mu_{v,s}$ and $k_{v,s}$ for hydrogen with saturation temperature obtained by means of the preceding technique. Similar plots are also given for nitrogen in figure 2(c) and freon 113 in figure 2(d).

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TABLE I. - RANGES OF VARIABLES AND PARAMETERS USED IN PRESENT STUDY (NOMINAL VALUES)

Reference	Fluid	Inside tube diameter, in.	Heated tube length, in.	Inlet pressure, lb/sq in. abs	Heat flux, q, Btu/(hr)(sq ft)	Mass velocity, G, lb-mass/(hr)(sq ft)	Fluid quality at burnout location, x_c
1	Hydrogen	0.555	16.125	30 to 74	0.004×10^6 to 0.05×10^6	0.0028×10^6 to 0.017×10^6	0 to 0.95
1	Nitrogen	.555	16.125	47 to 56	.003 to .05	.015 to .056	.08 to .95
2	Hydrogen	.313	12.0	27 to 72	.118 to .53	.42 to 1.12	0
2	Hydrogen	.495	12.0	28 to 50	.085 to .425	.15 to .37	0
(a)	Hydrogen	.495	12.0	32 to 50	.039 to .214	.15 to .38	0
4	Freon 113	.18,.408	15.0	17 to 24	.014 to .042	.33 to .82	0

Reference	Fluid	Maximum film vaporization parameter, $(X_F)_{max}$	Vapor Reynolds number, Re_v	Experimental Nusselt number, Nu_{exp}	Heat-addition parameter, Γ	Boiling number, N_B
1	Hydrogen	1.0	0.035×10^6 to 0.22×10^6	120 to 300	700 to 3,000	0.265×10^{-6} to 0.275×10^{-6}
1	Nitrogen	1.0	.05 to .12	165 to 265	400 to 1,100	.49
2	Hydrogen	.71	3.5 to 9.2	1000 to 2350	5300 to 23,500	.26 to .30
2	Hydrogen	.83	2.0 to 4.3	800 to 1760	6000 to 30,000	.26 to .265
(a)	Hydrogen	.34	1.6 to 6.5	700 to 1500	2800 to 13,000	.26 to .265
4	Freon 113	.55	.16 to .90	94 to 258	178 to 450	1.19 to 1.39

[a]Unpublished NASA data.

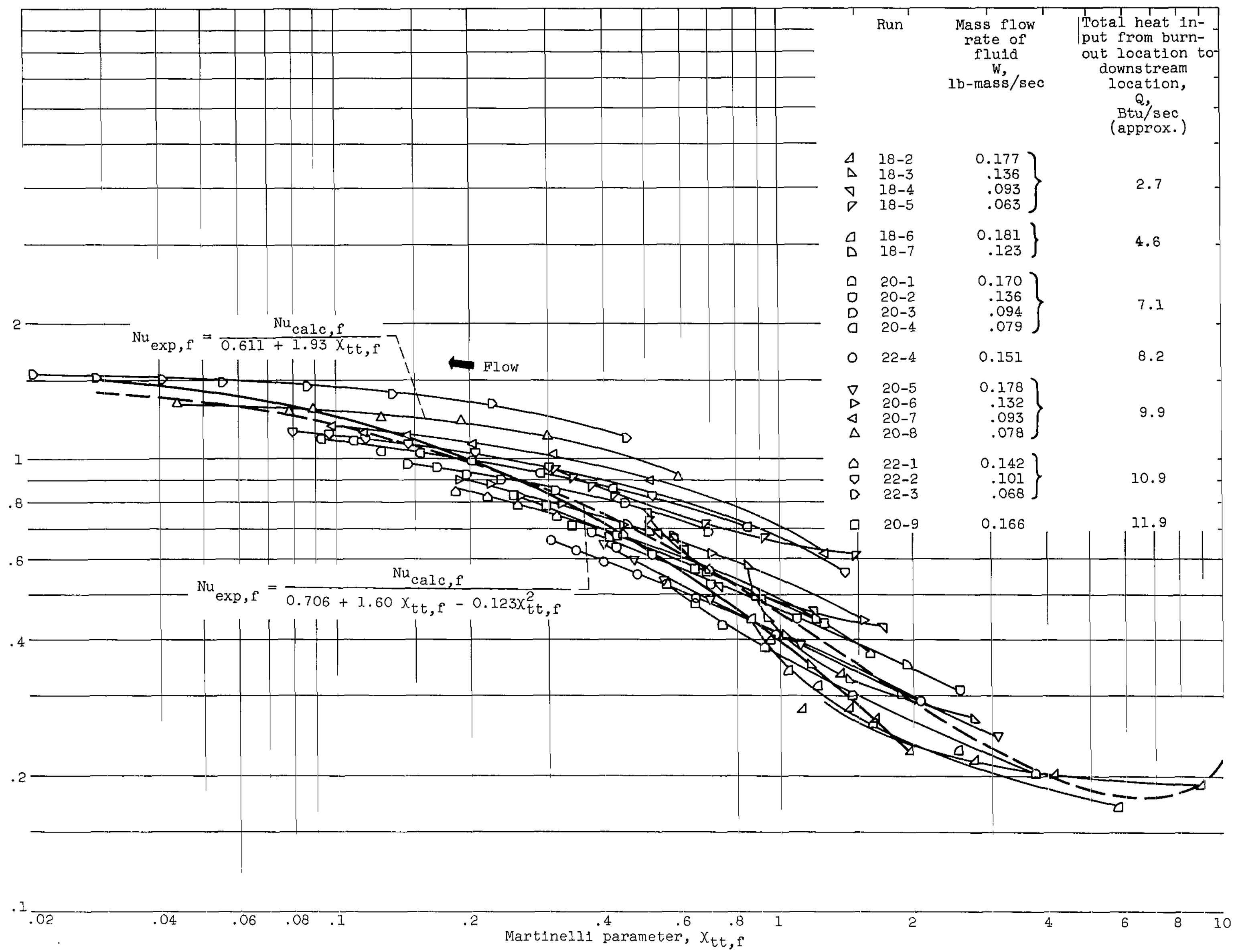
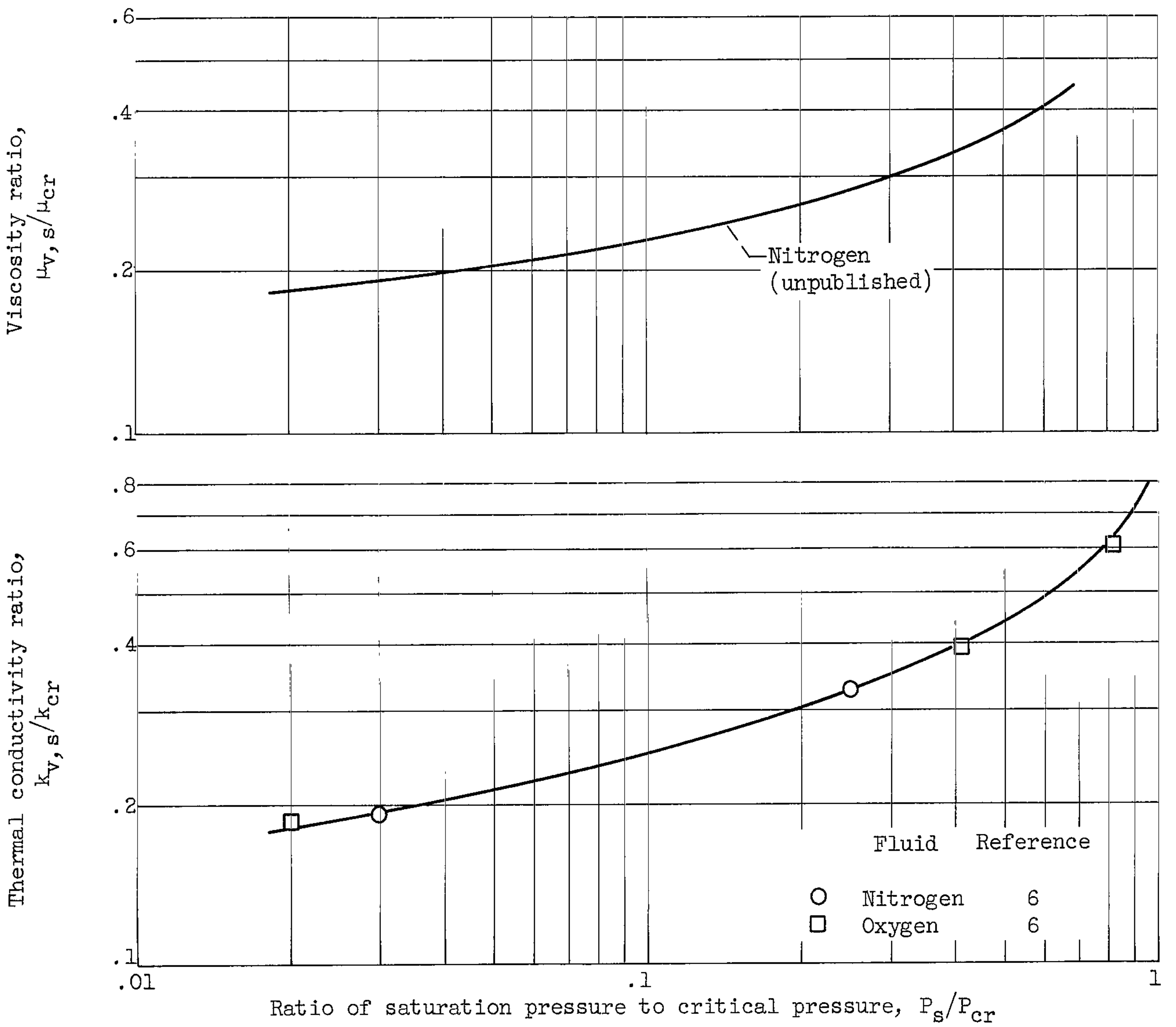
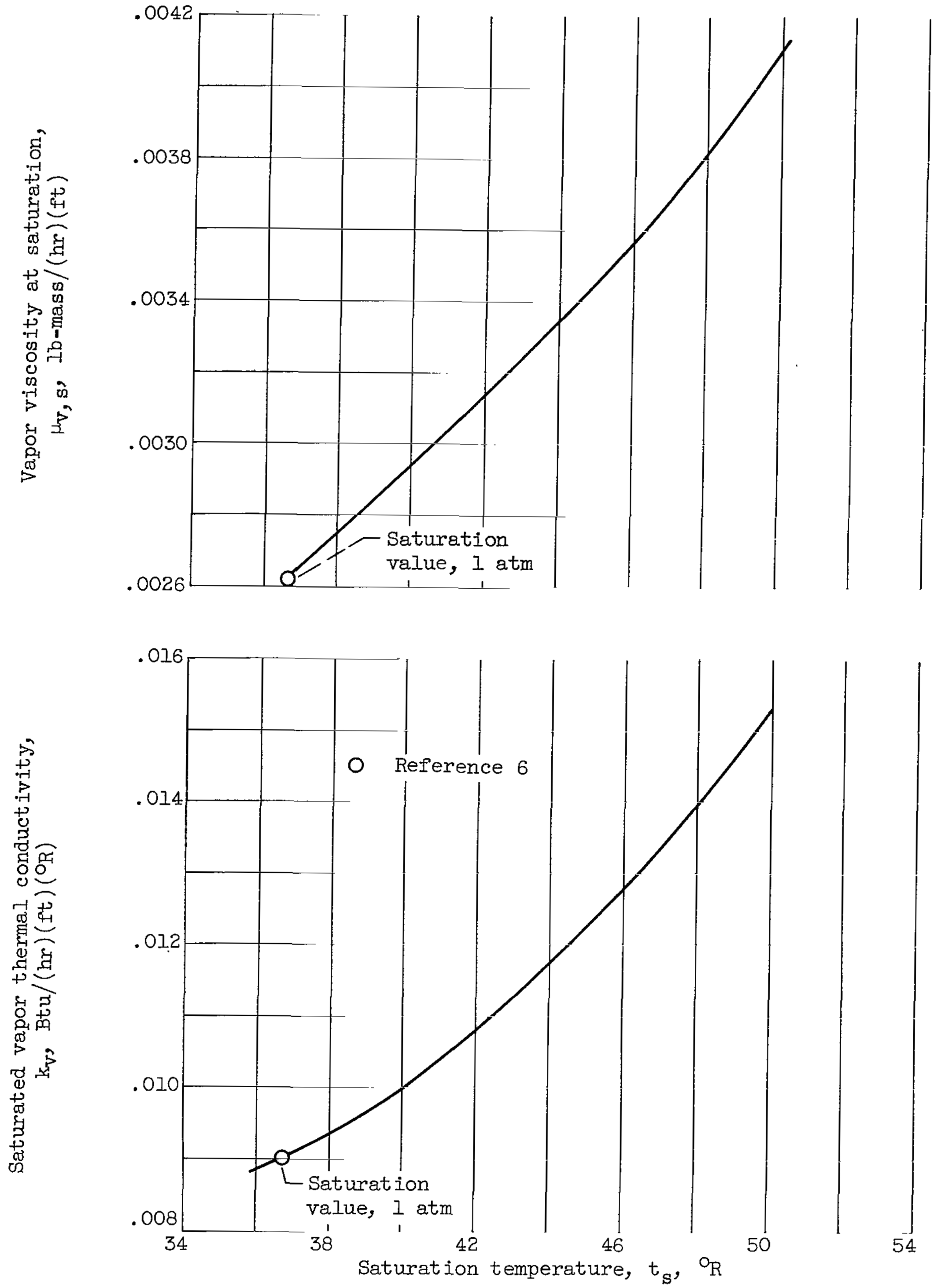


Figure 1. - Families of film-boiling heat-transfer data as functions of Martinelli parameter and Nusselt number ratio (ref. 2).



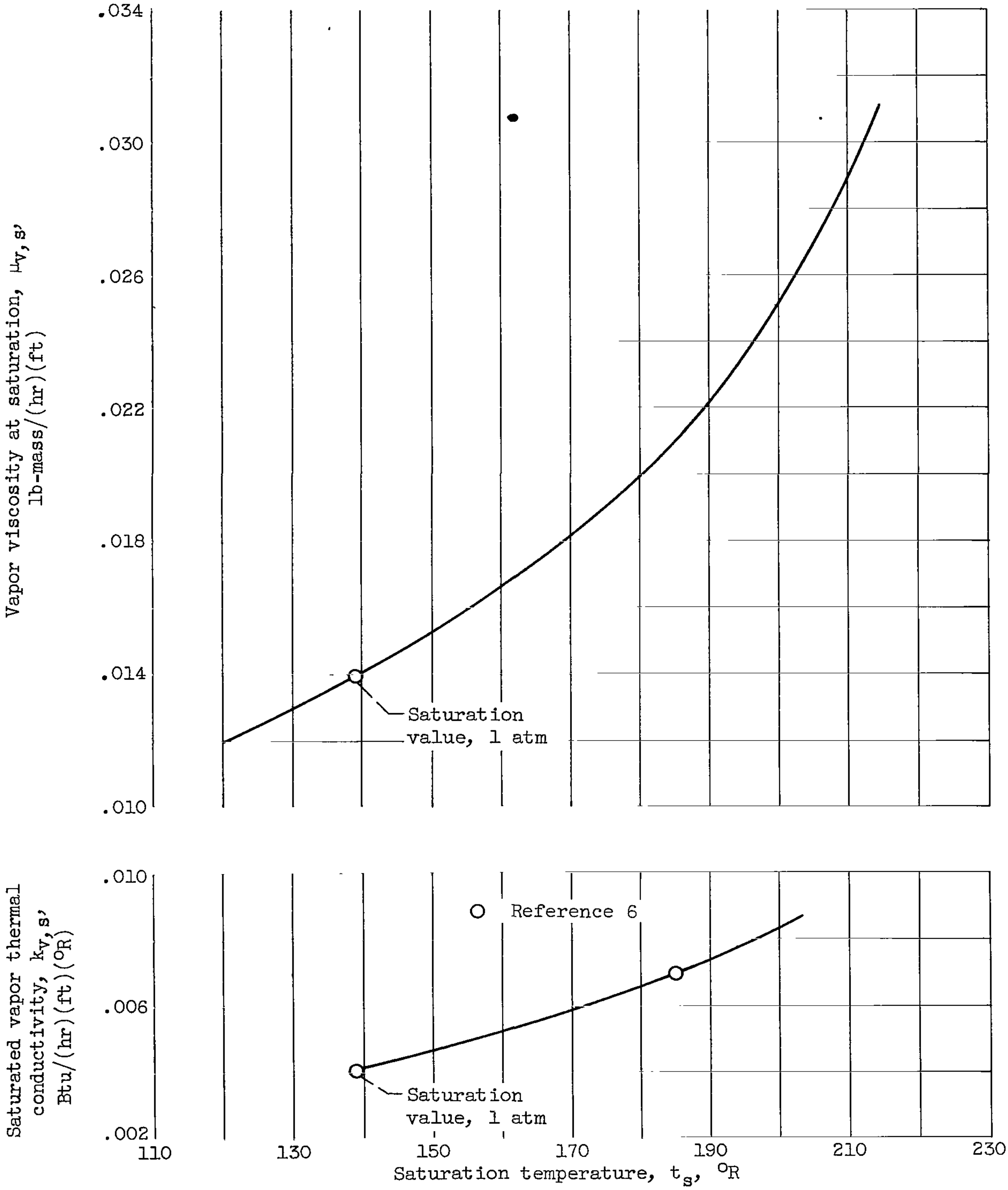
(a) Ratio of saturated vapor property value to property value at critical pressure as functions of ratio of saturation to critical pressure.

Figure 2. - Estimated saturated vapor viscosity and conductivity values for hydrogen, nitrogen, and freon 113.



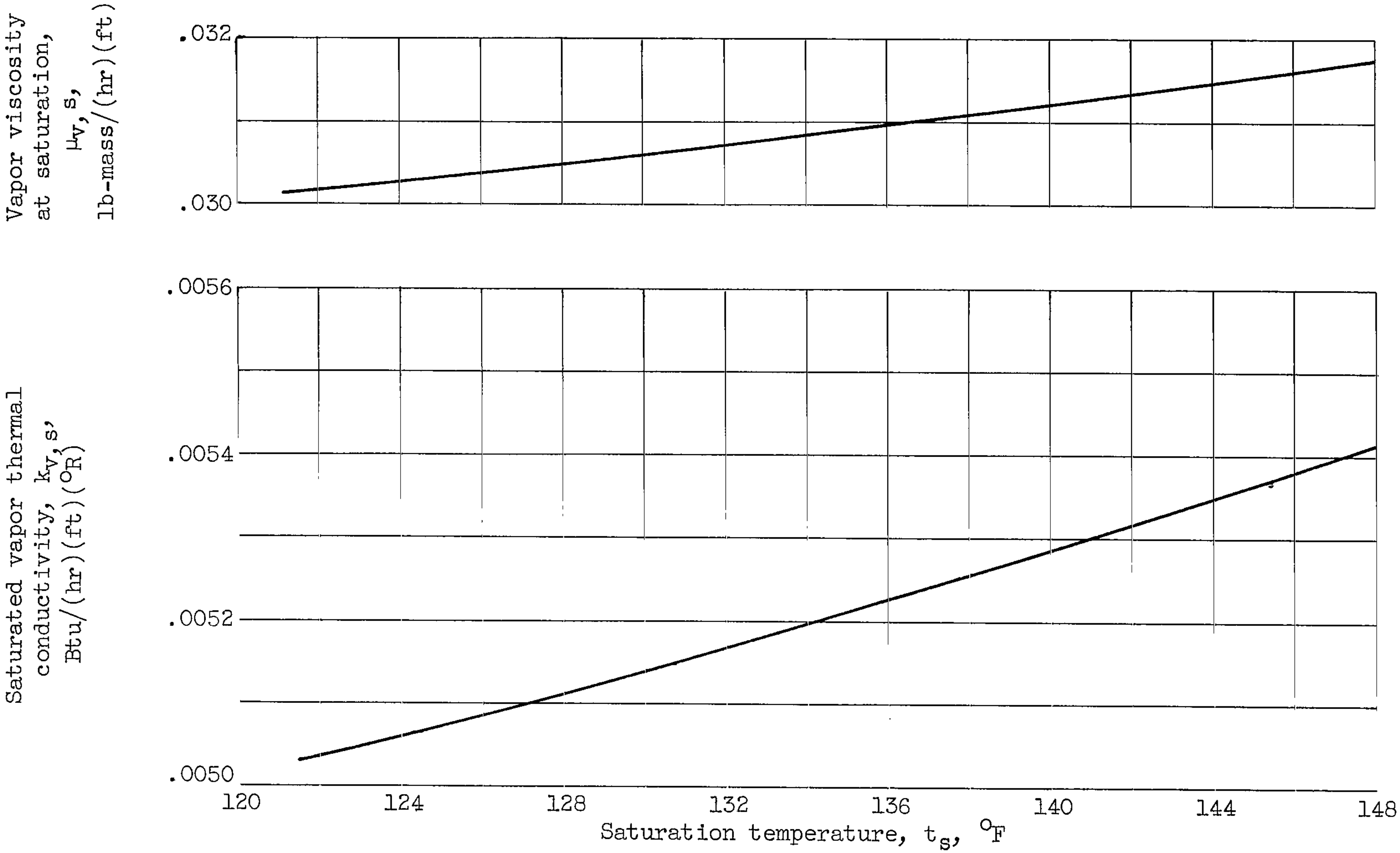
(b) Estimated saturated vapor properties for hydrogen.

Figure 2. - Continued. Estimated saturated vapor viscosity and thermal conductivity values for hydrogen, nitrogen, and freon 113.



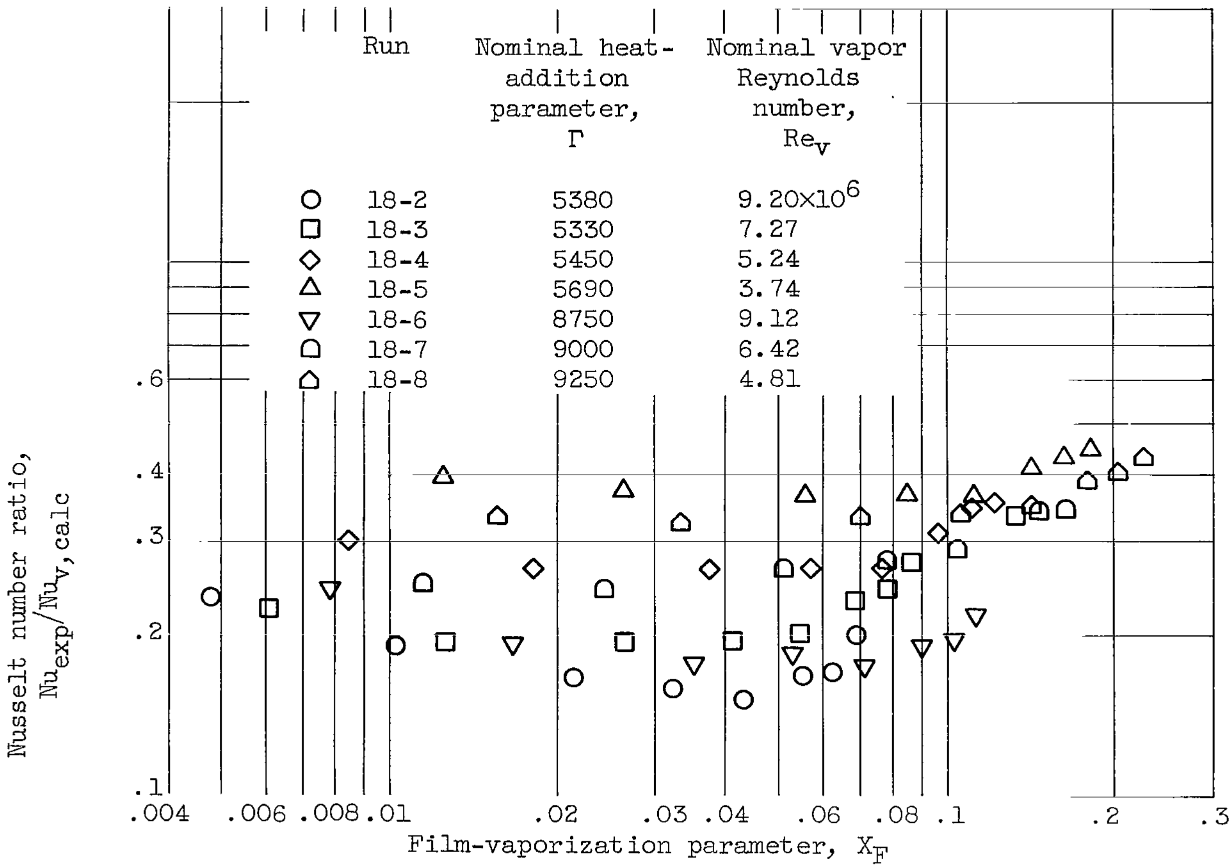
(c) Estimated saturated properties for nitrogen.

Figure 2. - Continued. Estimated saturated vapor viscosity and thermal conductivity values for hydrogen, nitrogen, and freon 113.



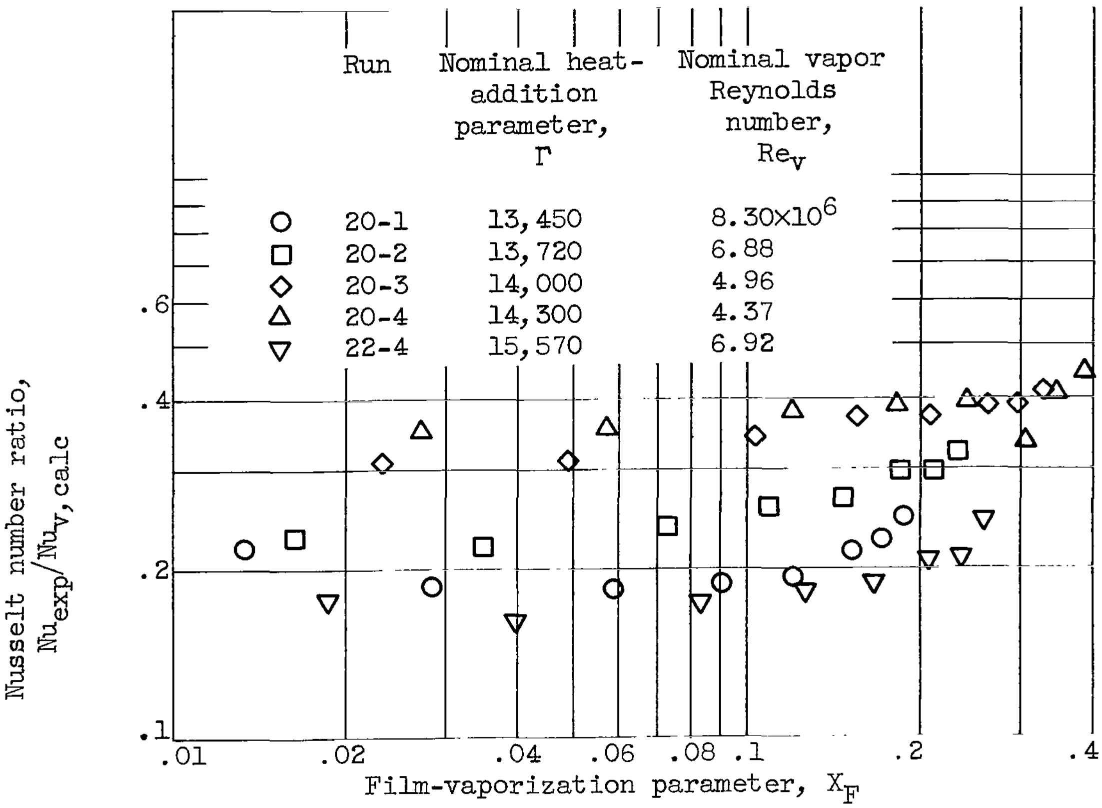
(d) Estimated saturation properties for freon 113.

Figure 2. - Concluded. Estimated saturation vapor viscosity and thermal conductivity values for hydrogen, nitrogen, and freon 113.



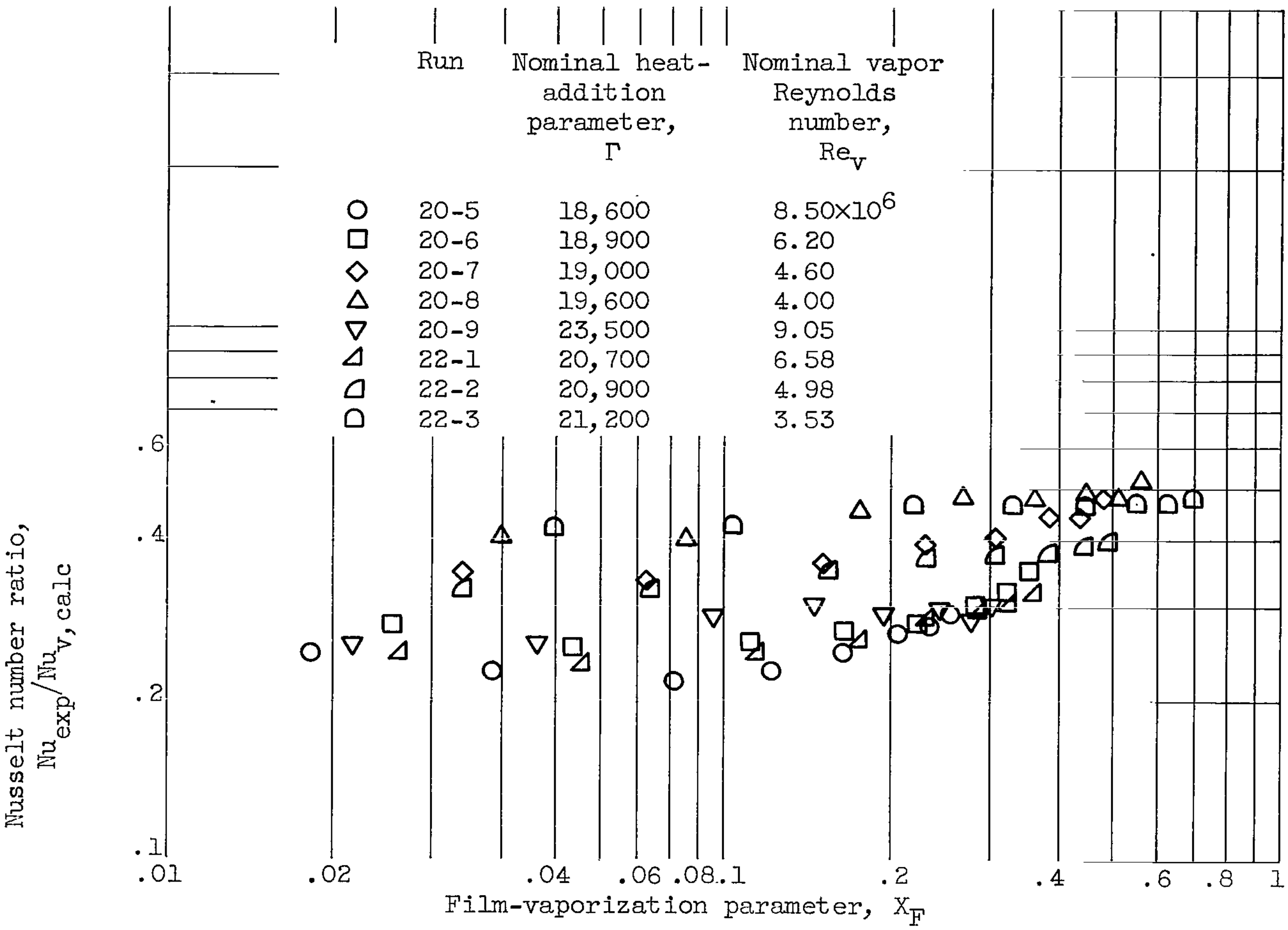
(a) 0.313-Inch inside diameter tube; range of heat-addition parameter, 5330 to 9250; published data.

Figure 3. - Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



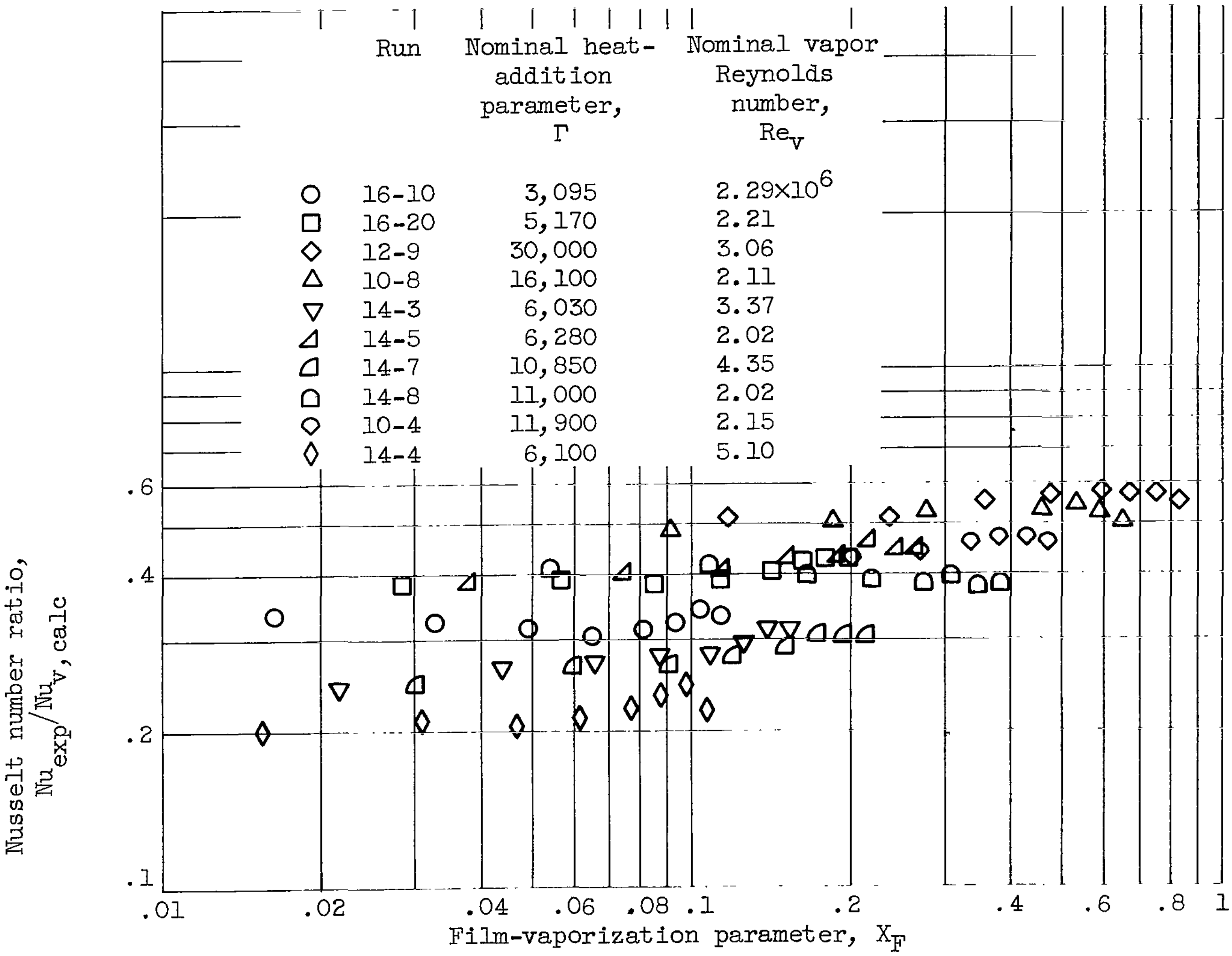
(b) 0.313-Inch inside diameter tube; range of heat-addition parameter, 13,450 to 15,570; published data.

Figure 3. - Continued. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



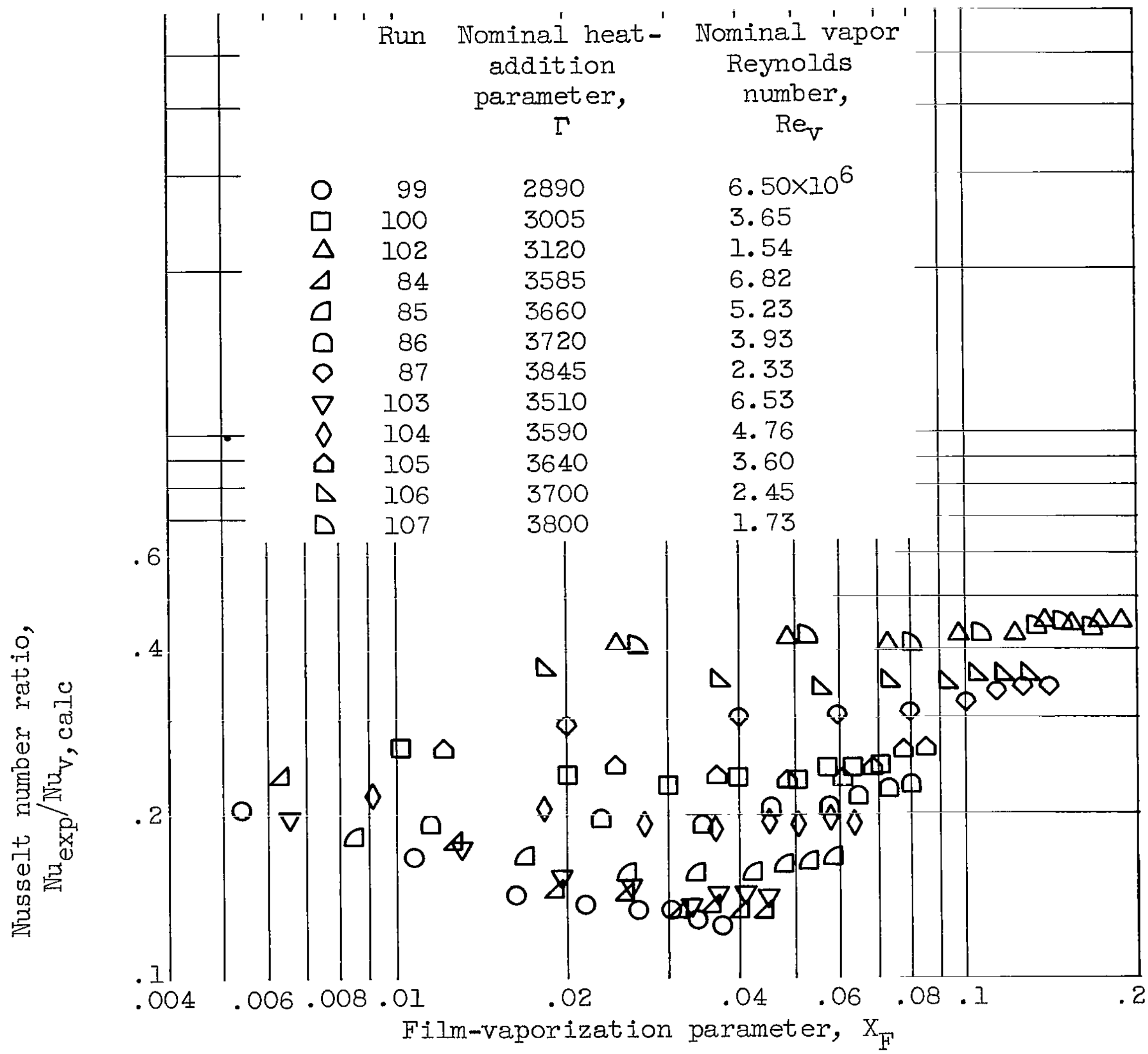
(c) 0.313-Inch inside diameter tube; range of heat-addition parameter, 18,600 to 23,500; published data.

Figure 3. - Continued. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



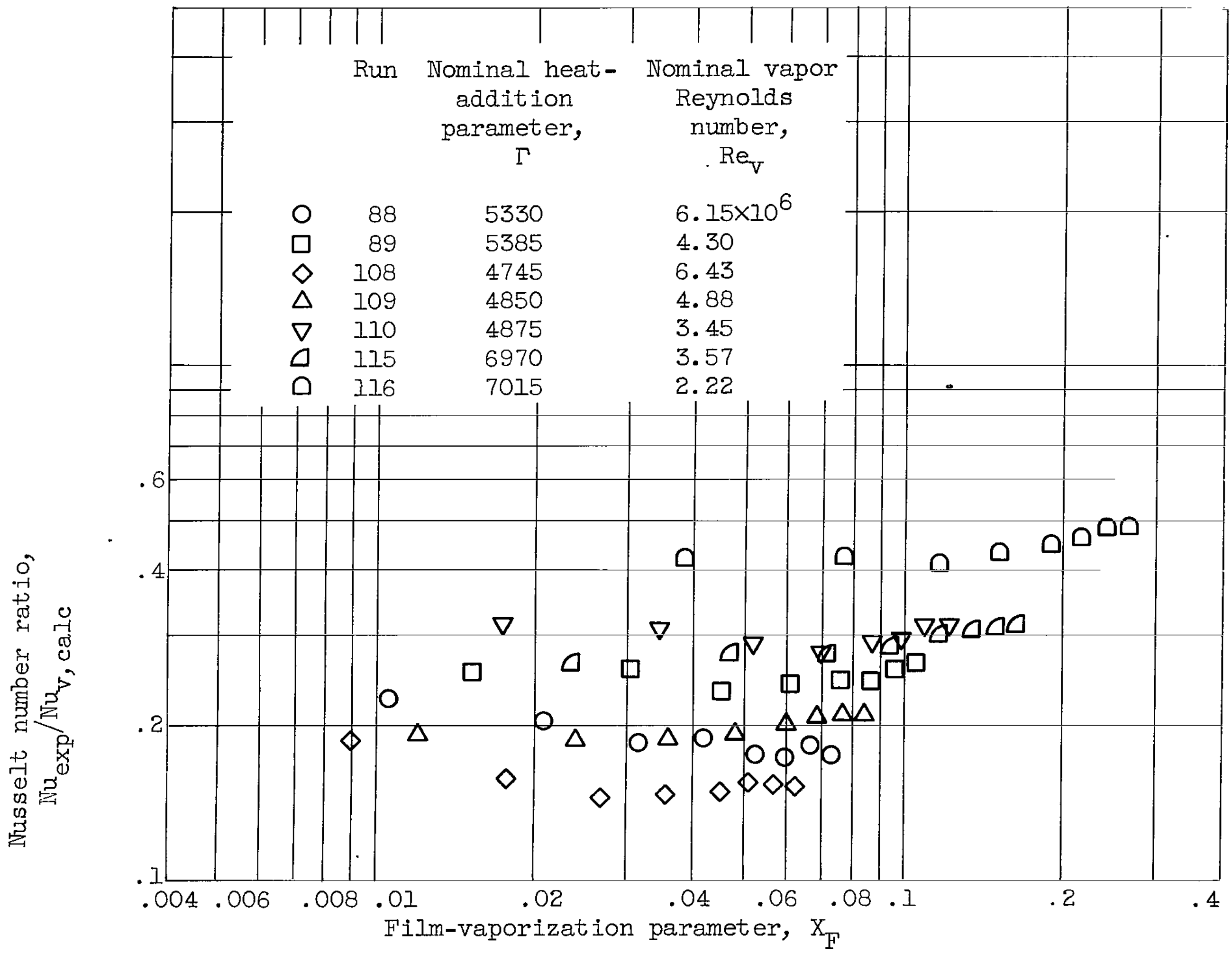
(d) 0.495-Inch inside diameter tube; range of heat-addition parameter, 3,095 to 30,000; published data.

Figure 3. - Continued. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2)



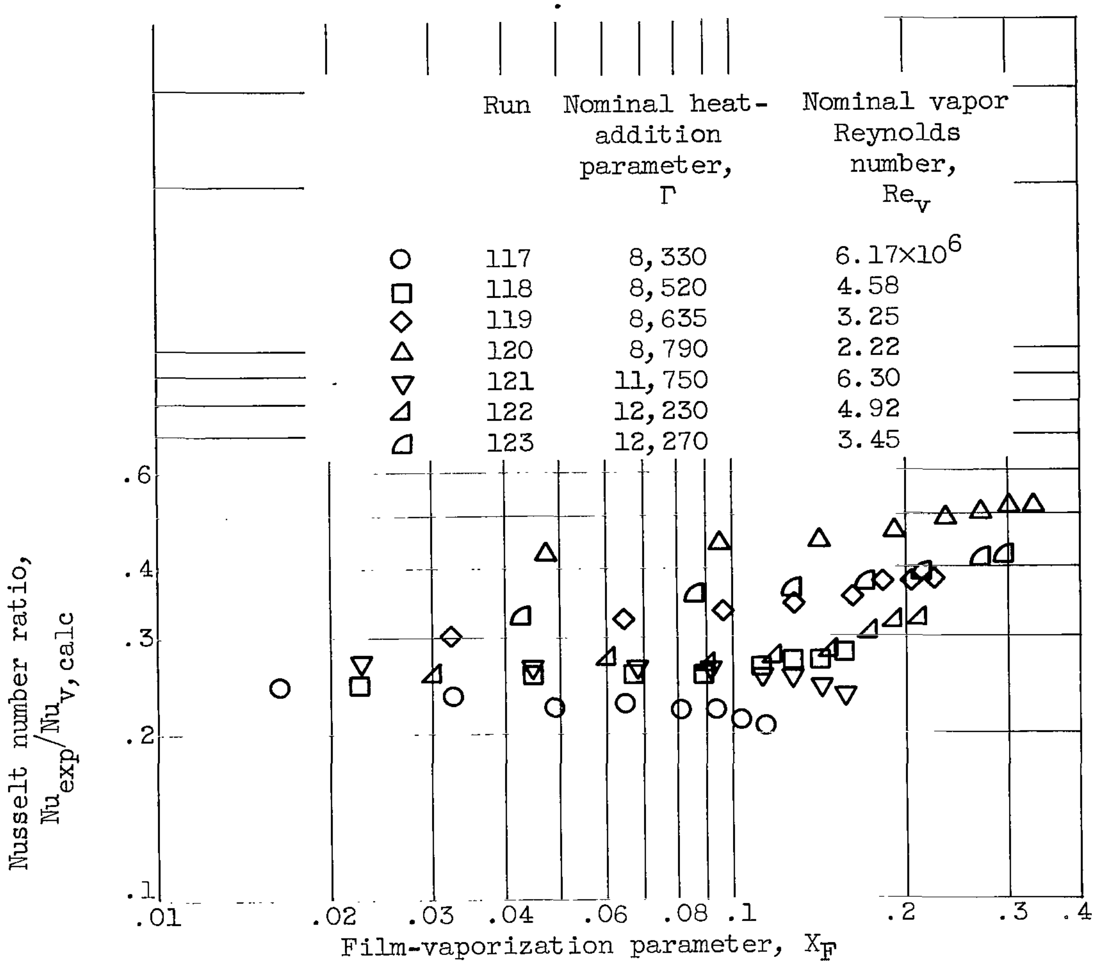
(e) 0.495-Inch inside diameter tube; range of heat-addition parameter, 2890 to 3845; unpublished data.

Figure 3. - Continued. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



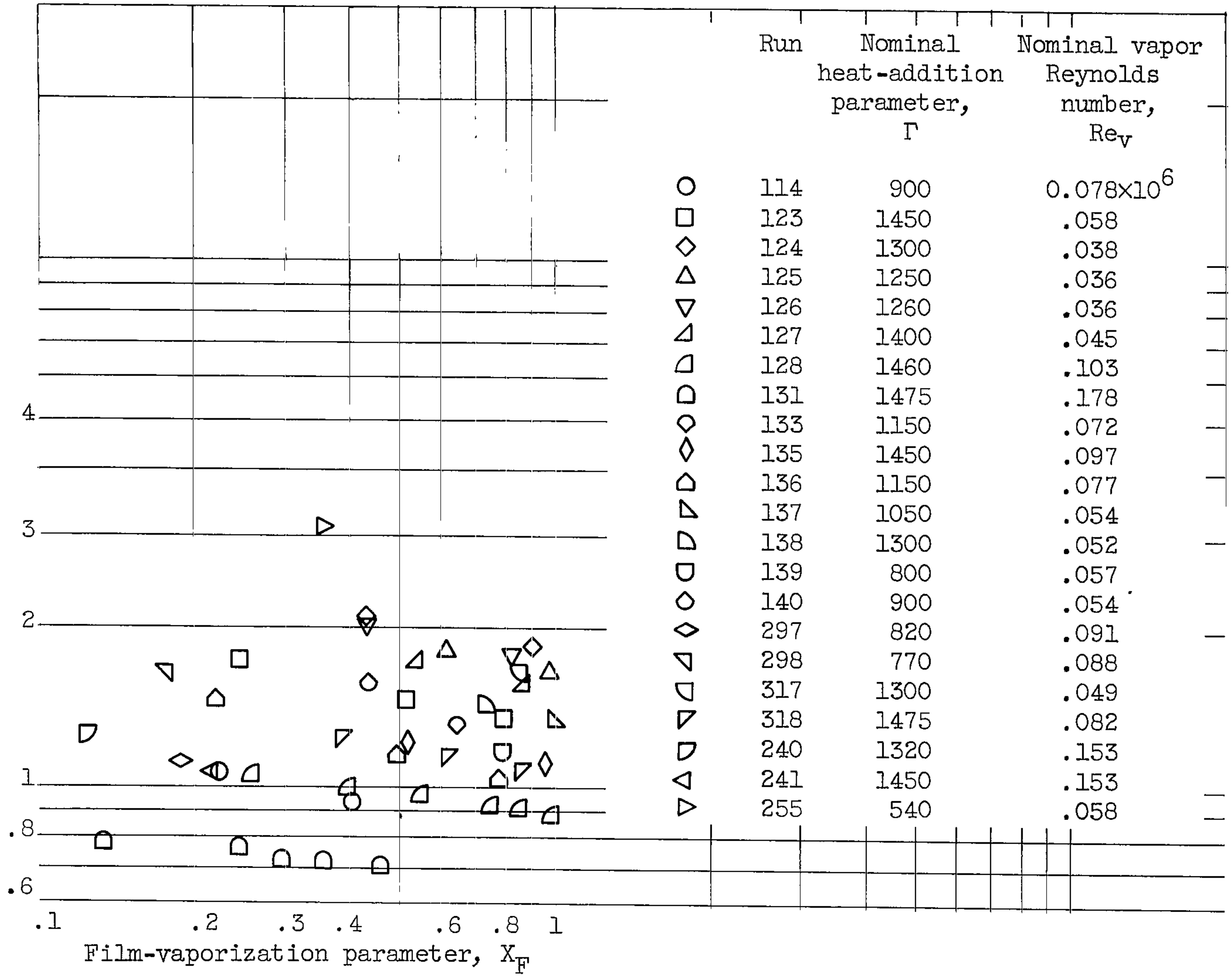
(f) 0.495-Inch inside diameter tube; range of heat-addition parameter, 4745 to 7015; unpublished data.

Figure 3. - Continued. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



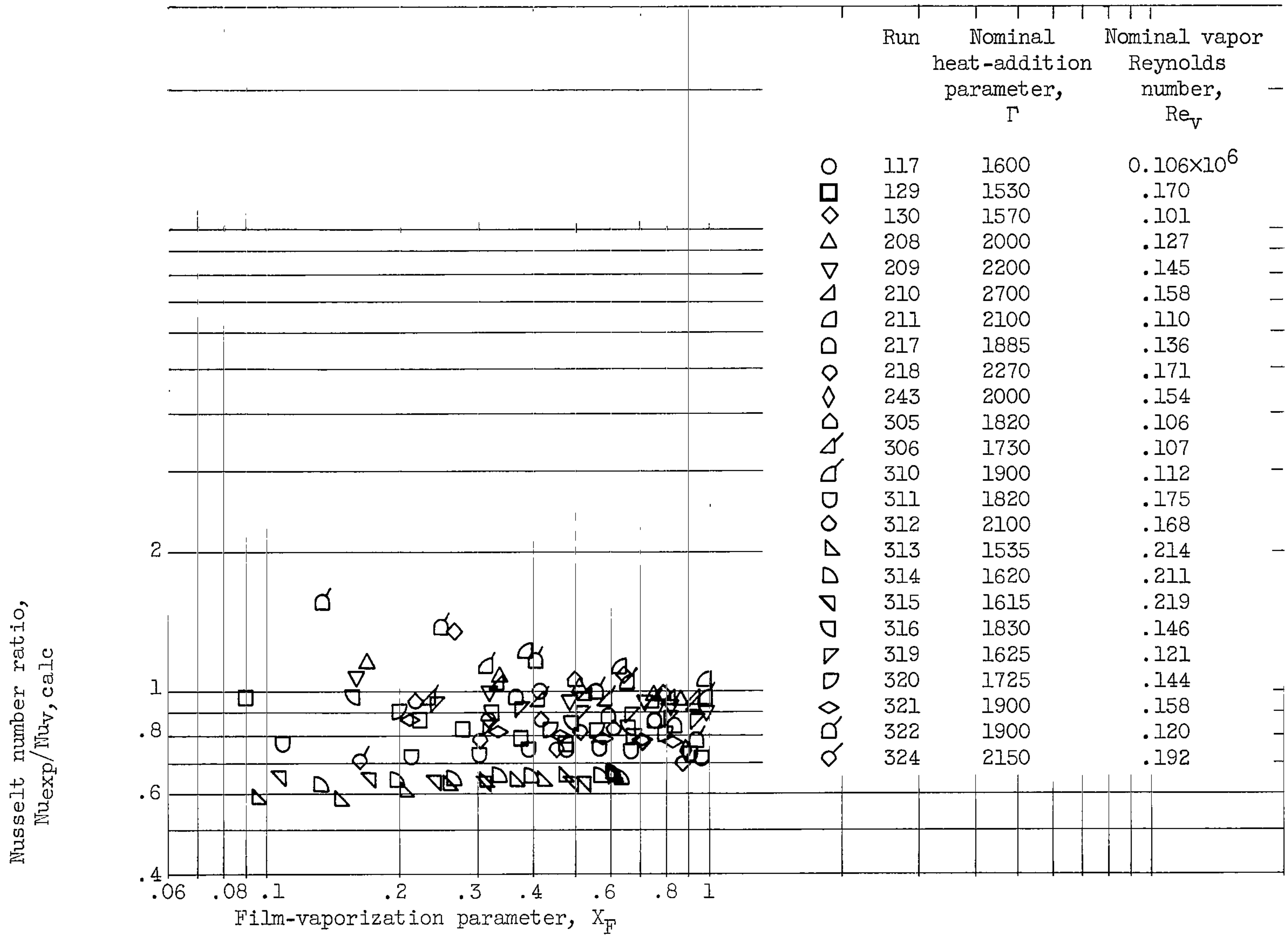
(g) 0.495-Inch inside diameter tube; range of heat-addition parameter, 8,330 to 12,270; unpublished data.

Figure 3. - Concluded. Variation of Nusselt number ratio with film-vaporization parameter for liquid hydrogen (ref. 2).



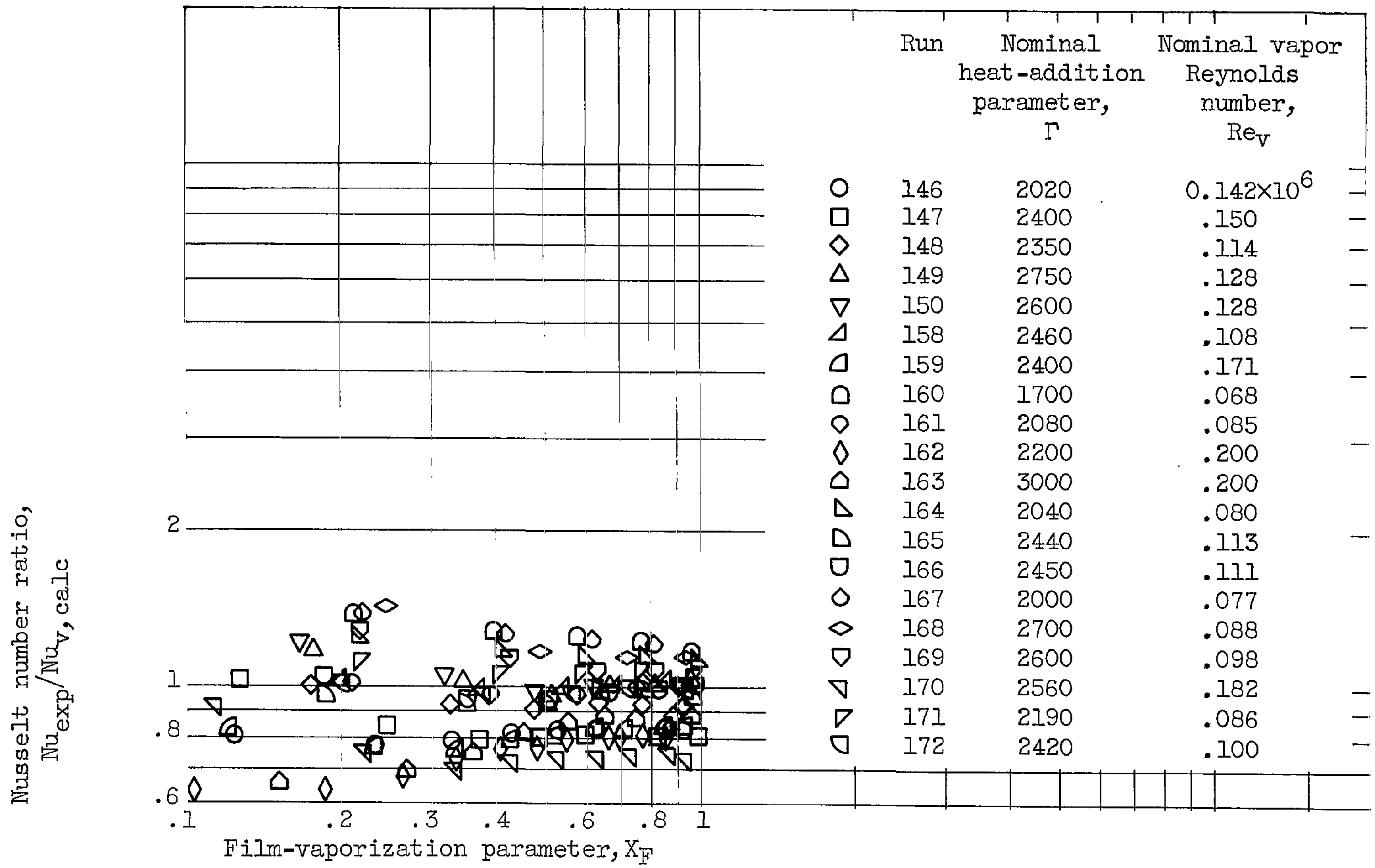
(a) Range of heat-addition parameter, 500 to 1500; burnout location downstream of heated tube entrance; liquid hydrogen; reference 1.

Figure 4. - Variation of Nusselt number ratio with film-boiling vaporization parameter.



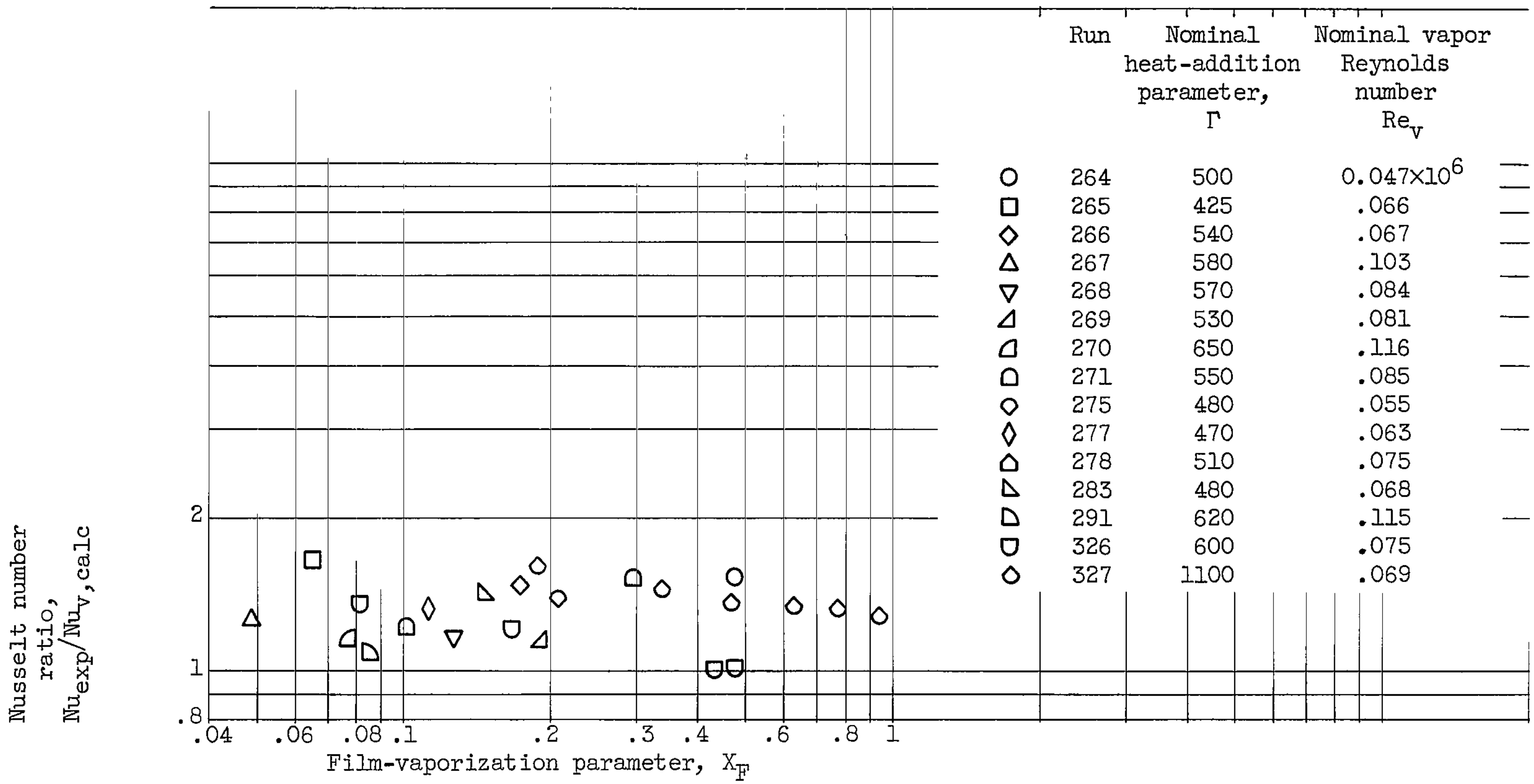
(b) Range of heat-addition parameter, 1500 to 2700; burnout location downstream of heated tube entrance; liquid hydrogen; reference 1.

Figure 4. - Continued. Variation of Nusselt number ratio with film-vaporization parameter.



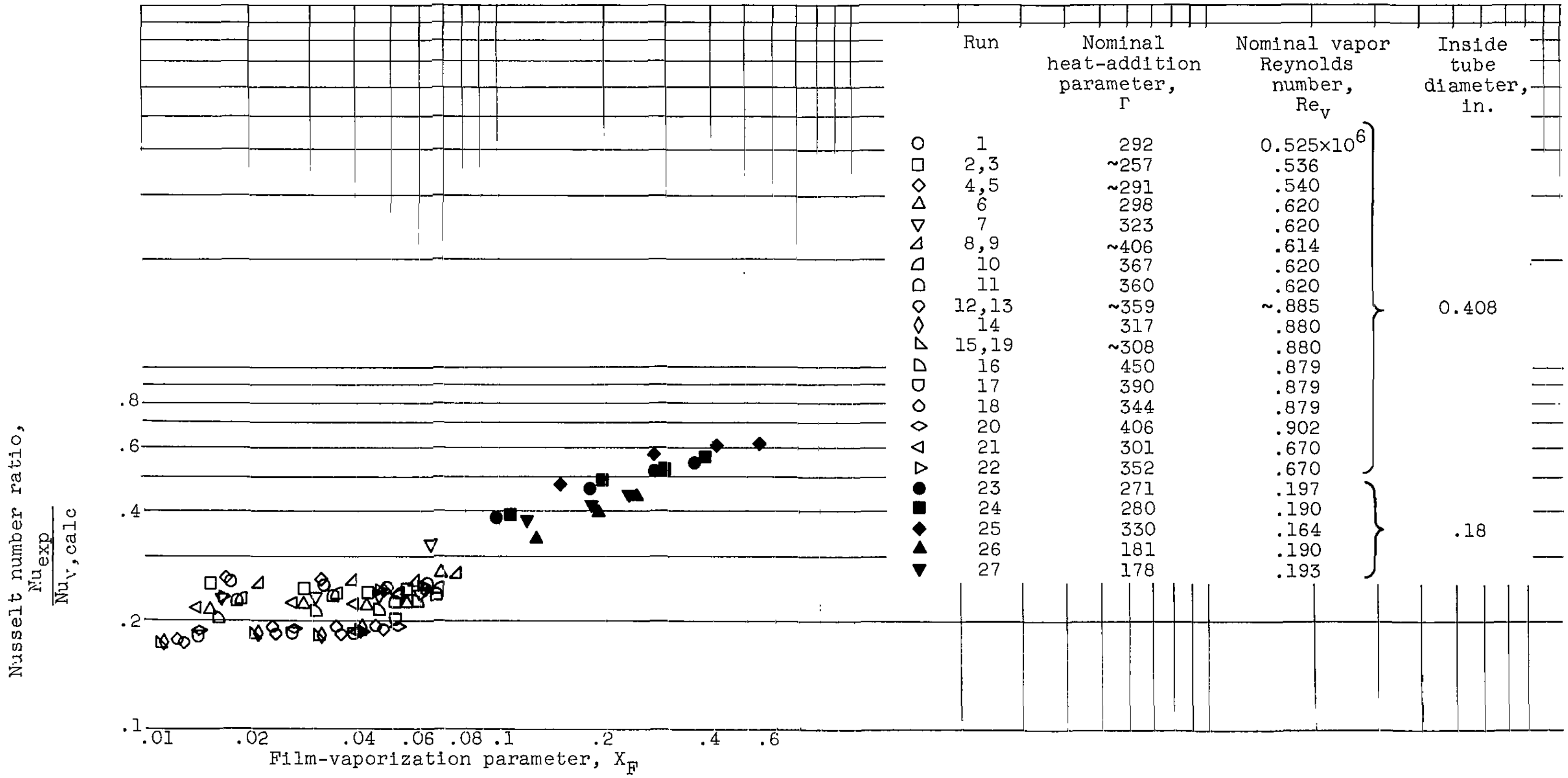
(c) Range of heat-addition parameter; 1700 to 3000; burnout location near tube entrance; liquid hydrogen; reference 1.

Figure 4. - Continued. Variation of Nusselt number ratio with film-vaporization parameter.



(d) Range of heat-addition parameter, 425 to 1100; burnout location downstream of heated tube entrance; liquid nitrogen; reference 1.

Figure 4. - Continued. Variation of Nusselt Number ratio with film-vaporization parameter.



(e) Freon 113; reference 4.

Figure 4. - Concluded. Variation of Nusselt number ratio with film-vaporization parameter.

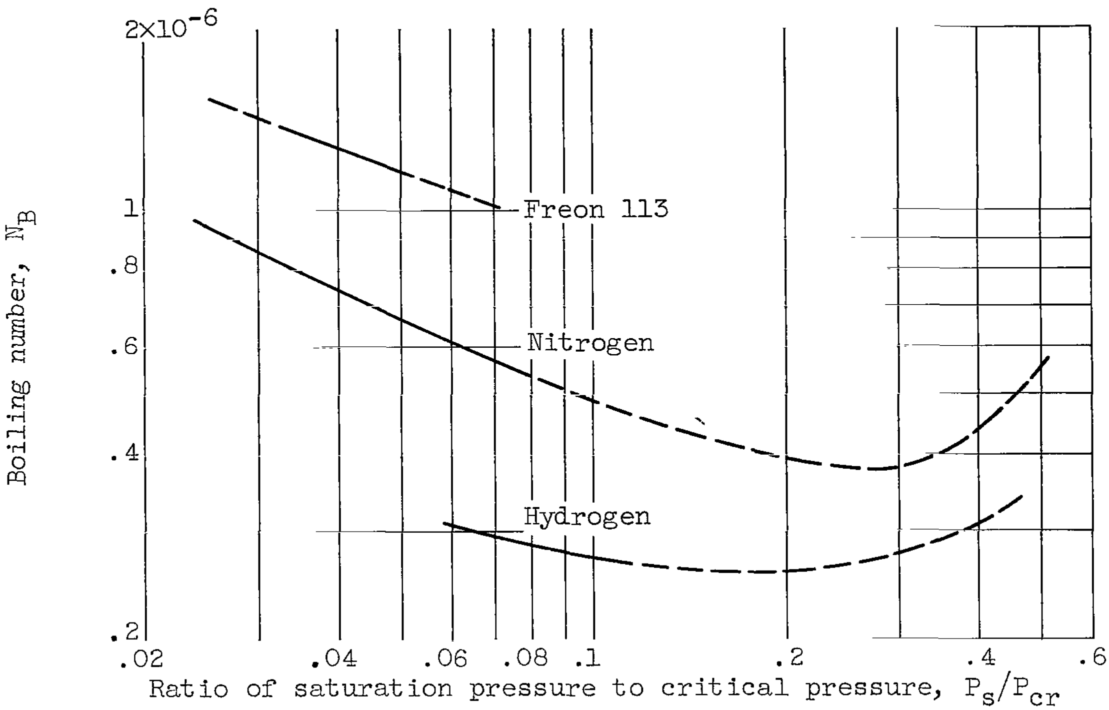
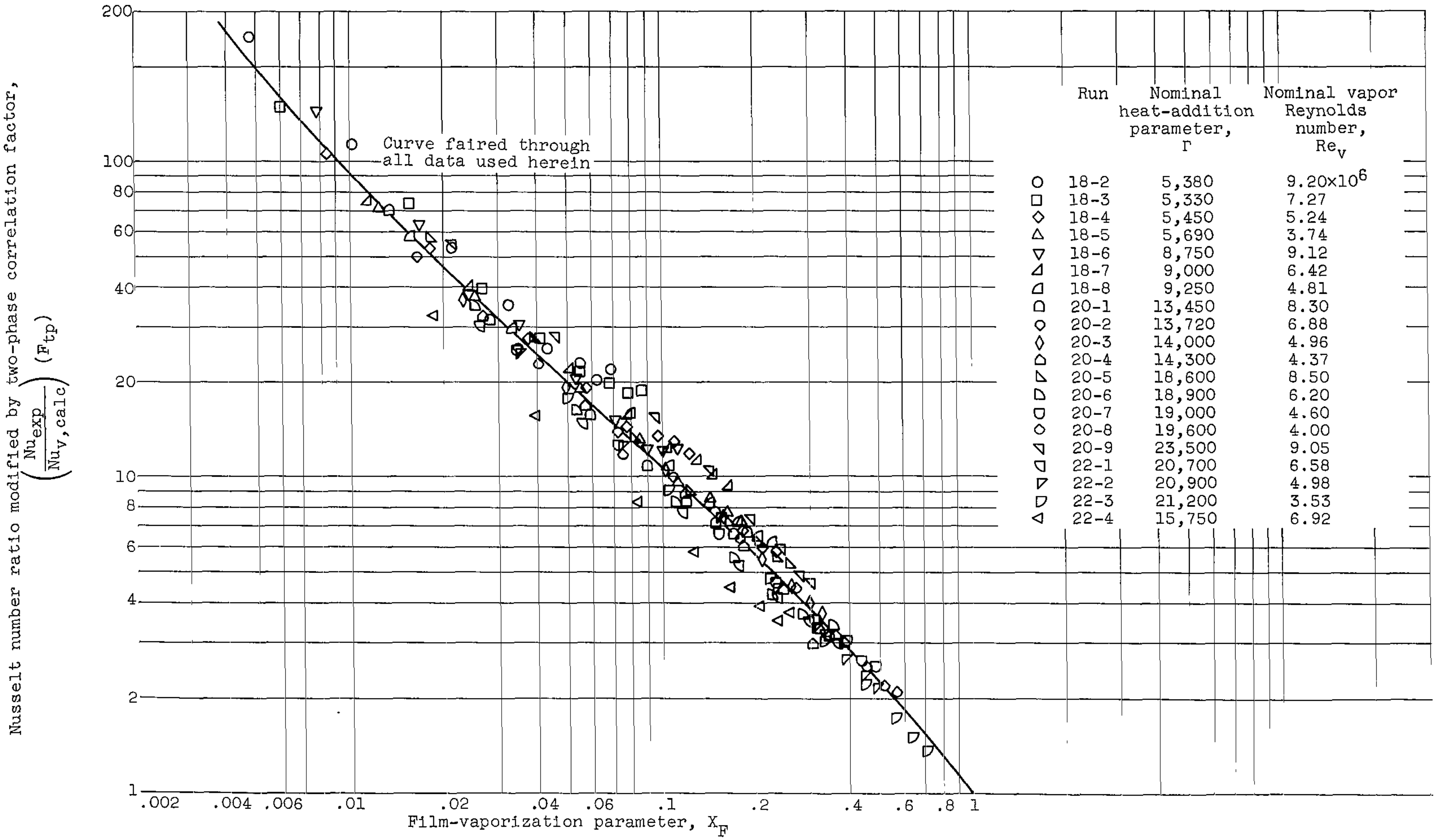
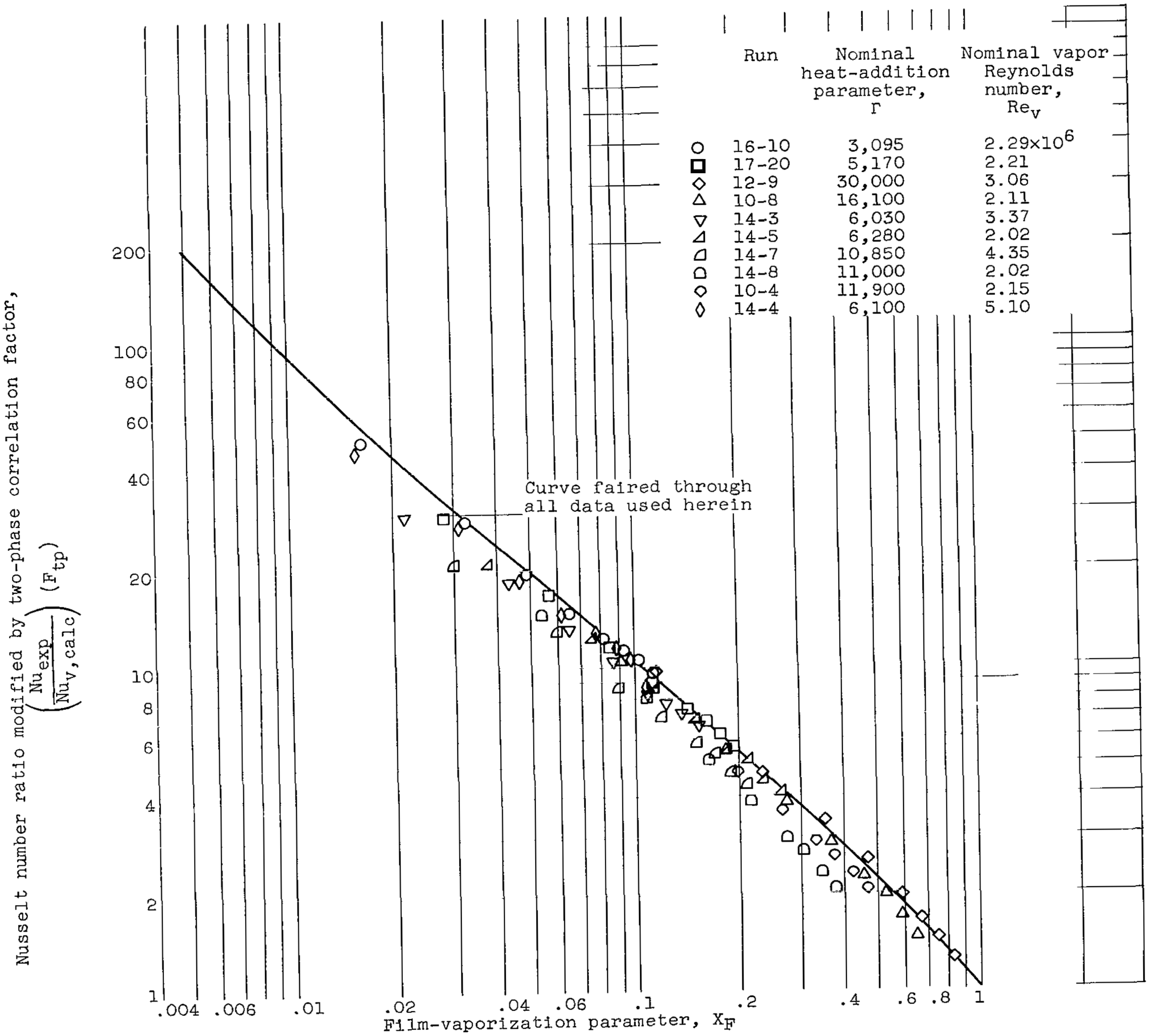


Figure 5. - Variation of boiling number for hydrogen, nitrogen, and freon 113 with ratio of saturation pressure to critical pressure.



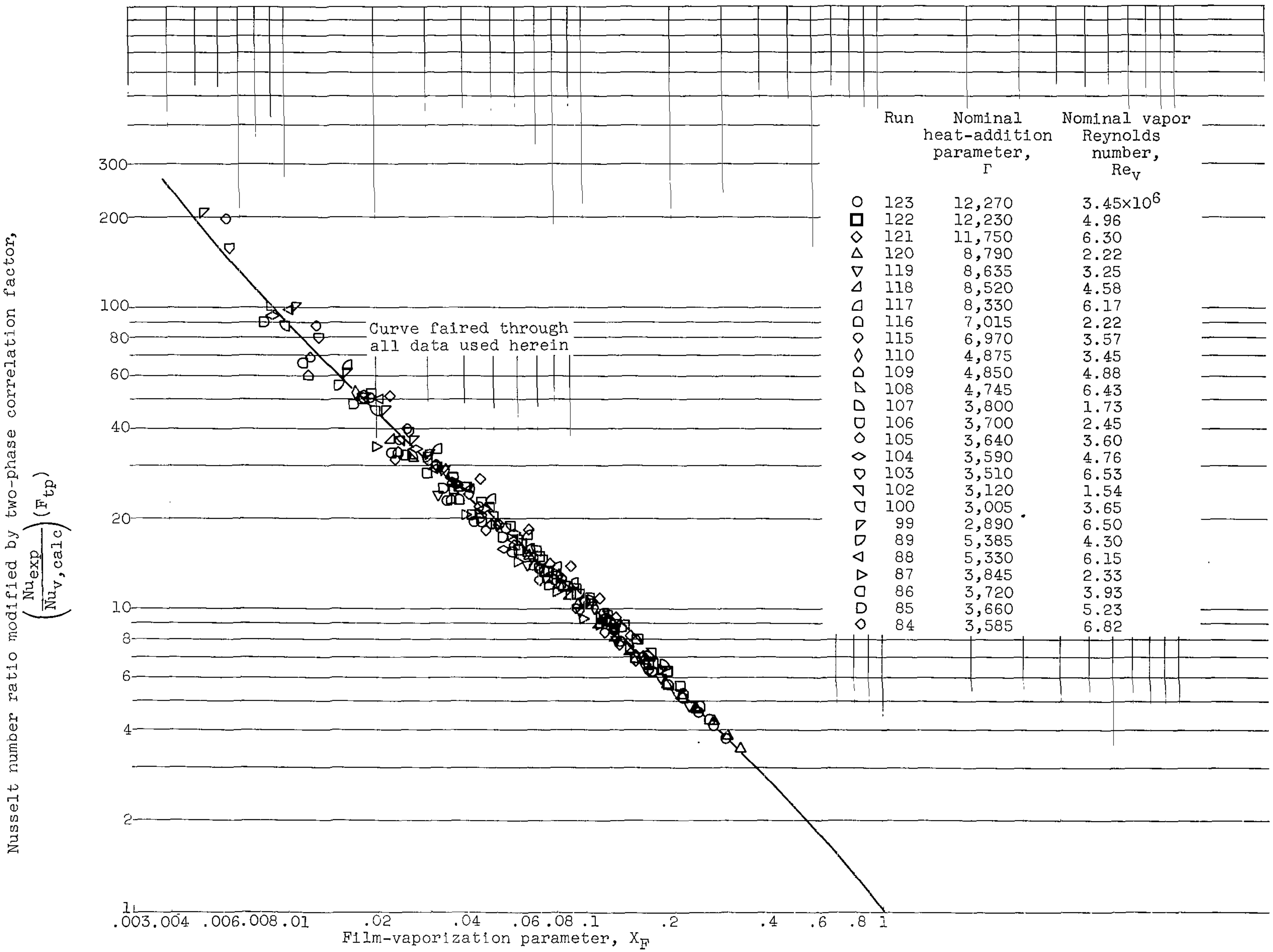
(a) 0.313-Inch inside diameter tube; $L_e/D > 3.5$; liquid hydrogen; reference 2.

Figure 6. - Correlation of film-vaporization parameter with modified Nusselt number ratio.



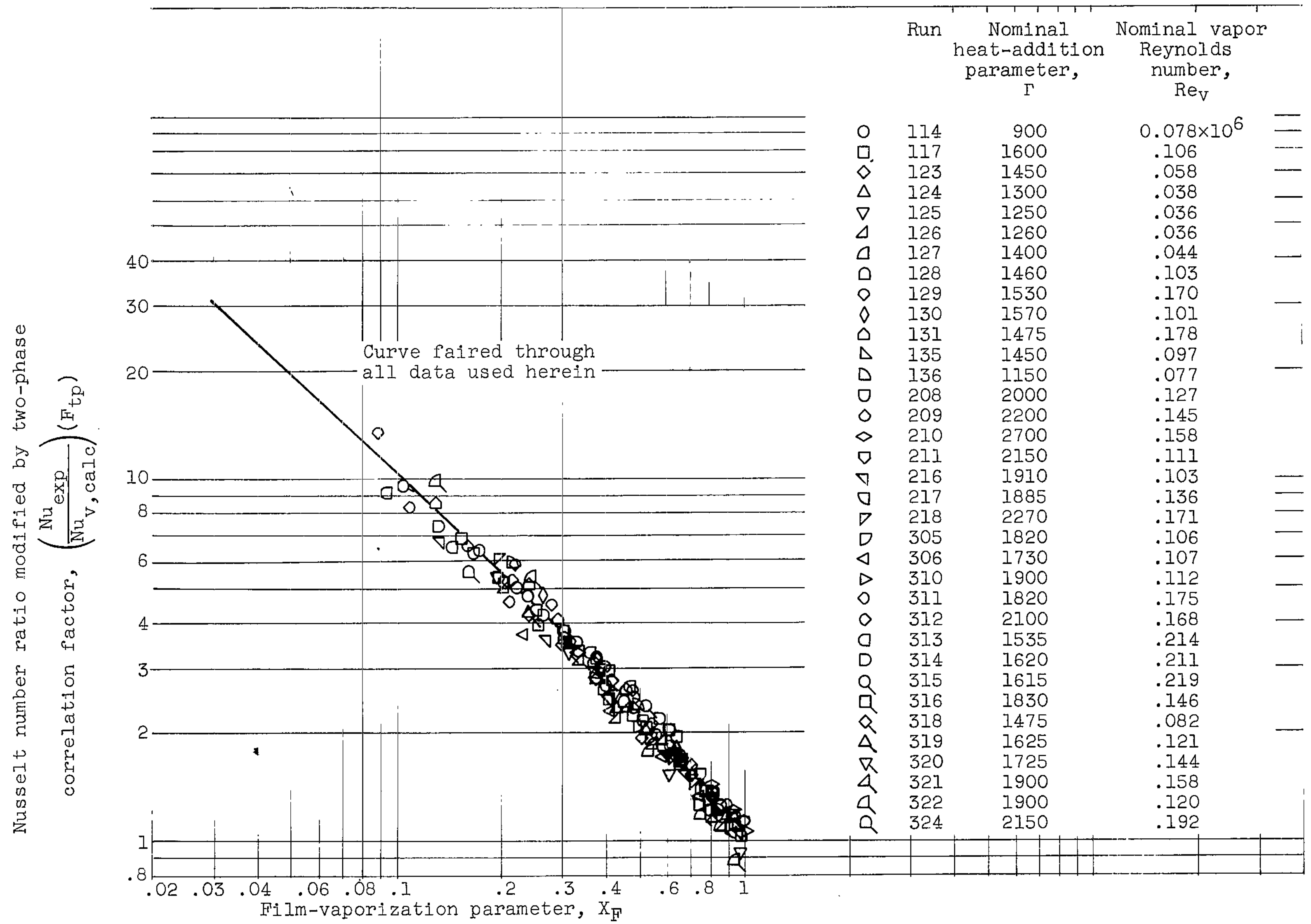
(b) 0.495-Inch inside diameter tube; $L_e/D > 3.5$; liquid hydrogen; reference 2.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



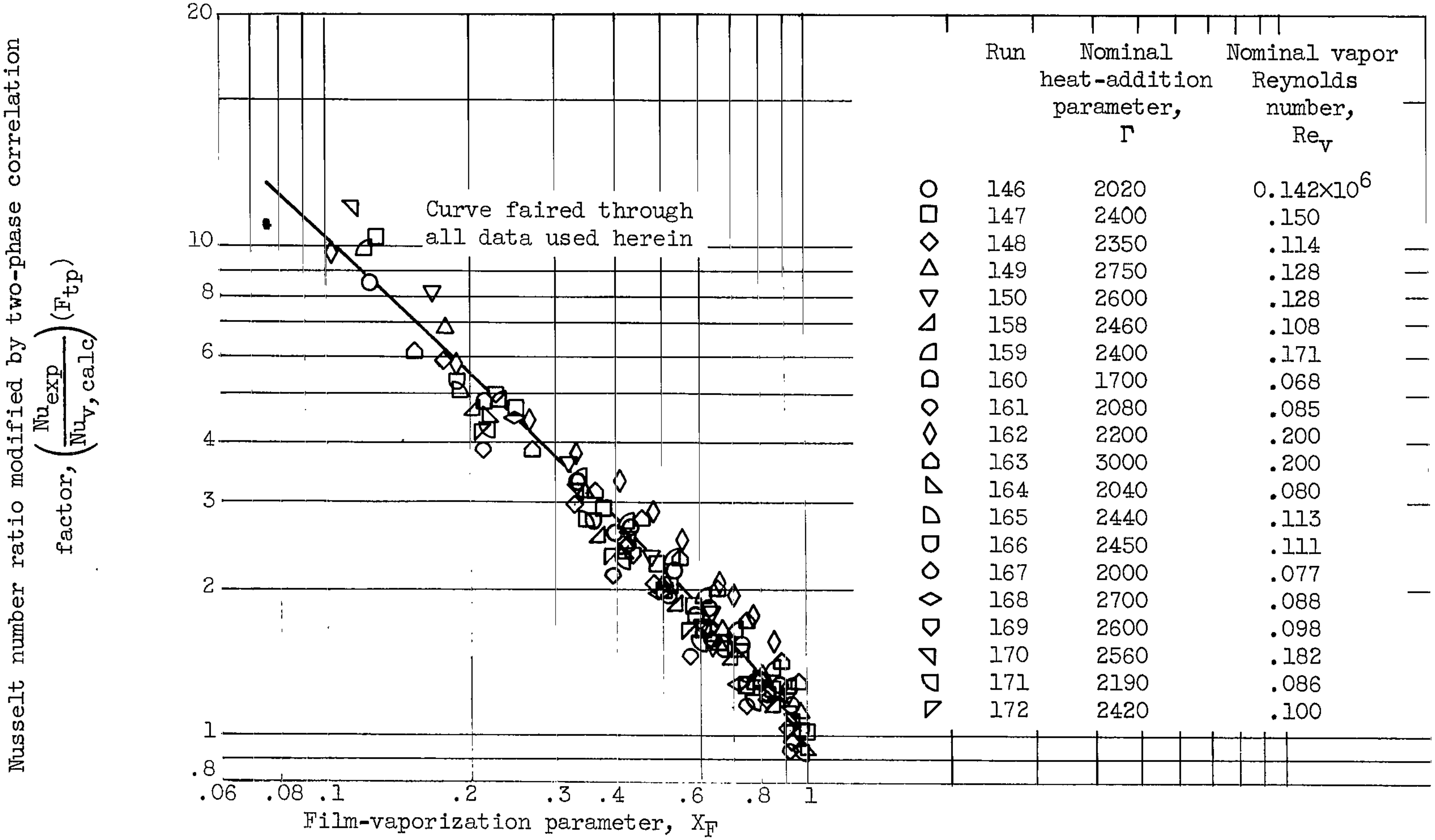
(c) 0.495-Inch inside diameter tube; $L_e/D > 3.5$; liquid hydrogen; unpublished NASA data.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



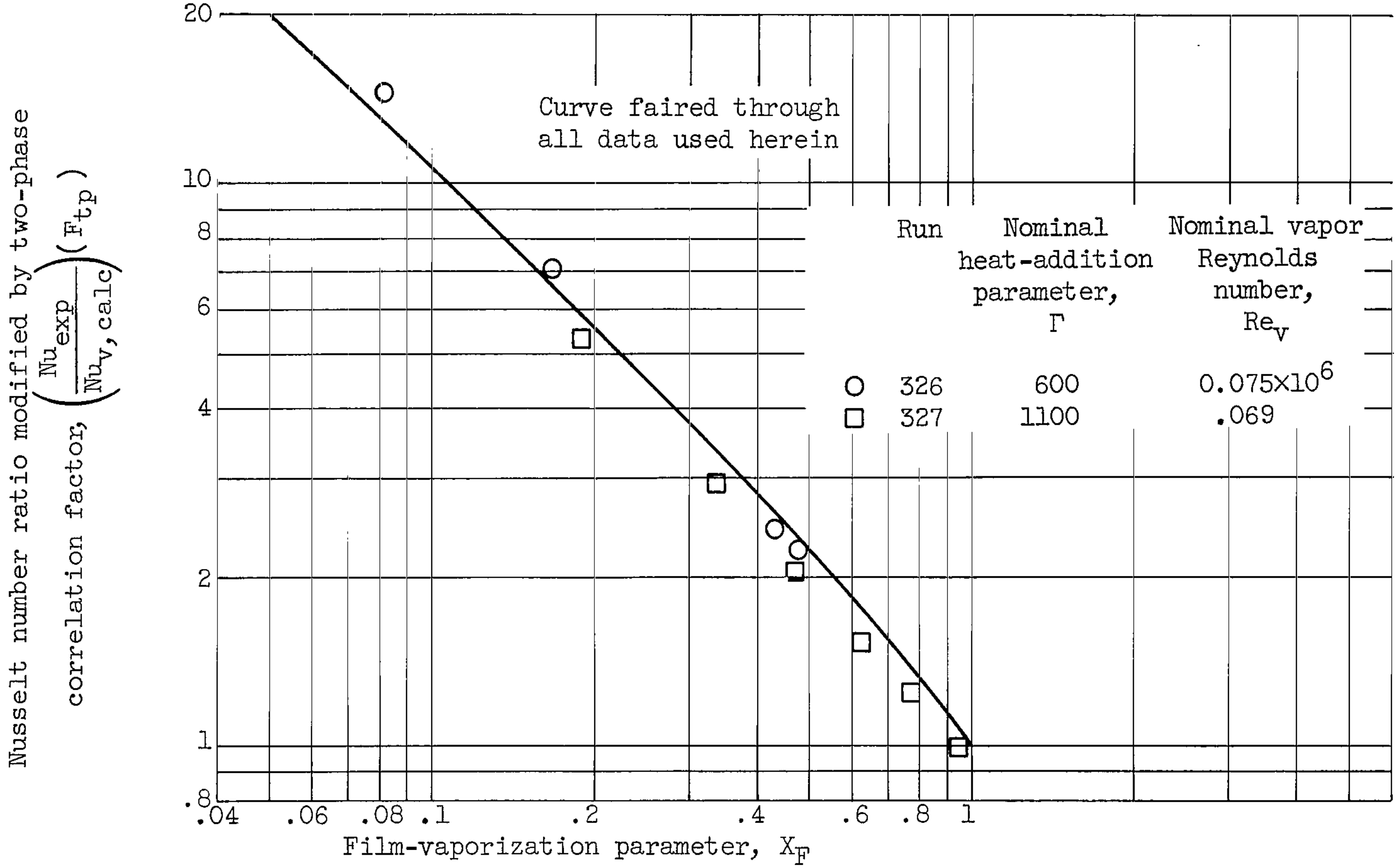
(d) 0.555-Inch inside diameter tube; $L_e/D > 3.5$; liquid hydrogen; reference 1.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



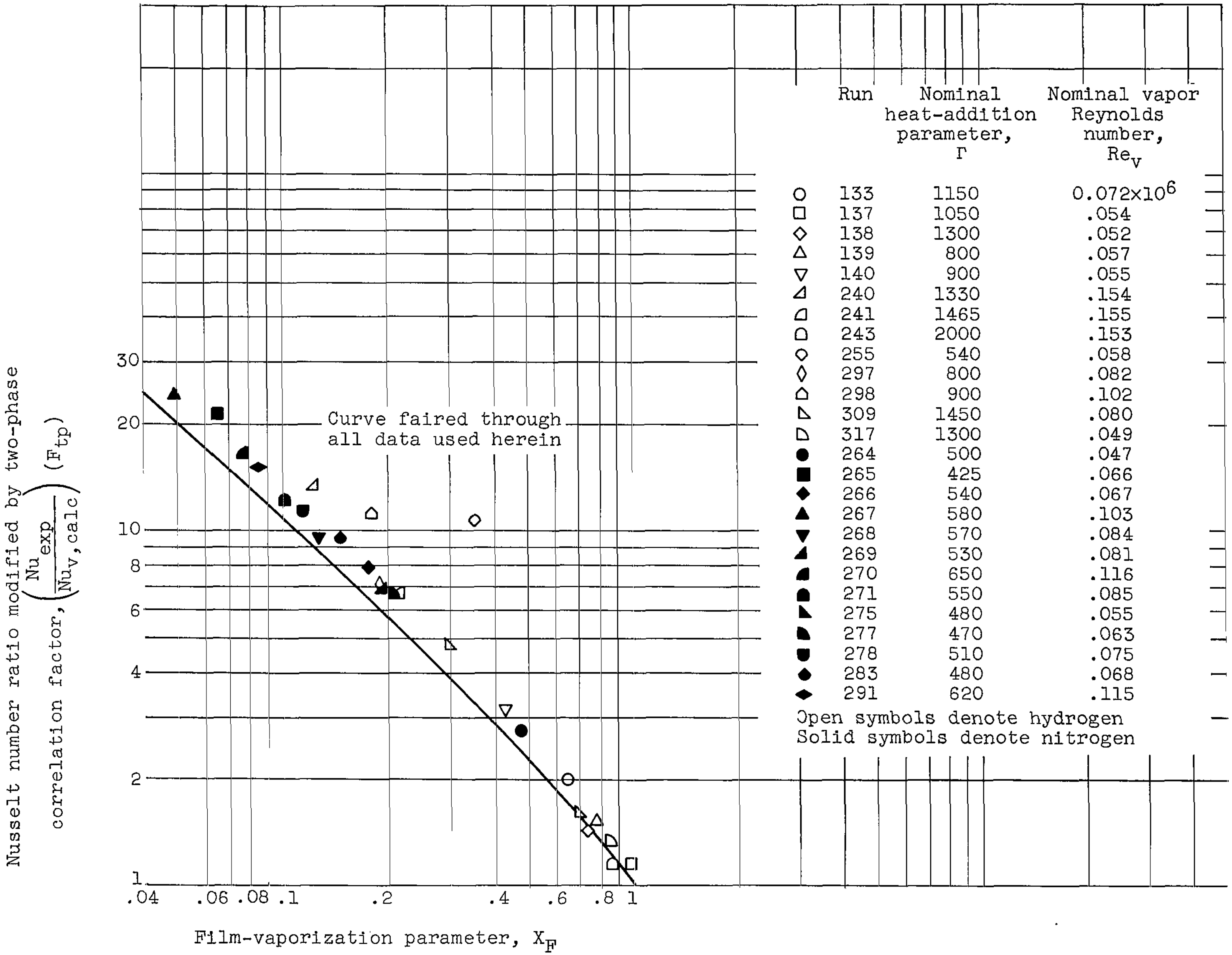
(e) 0.555-Inch inside diameter tube; $L_e/D \cong 0.9$; liquid hydrogen; reference 1.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



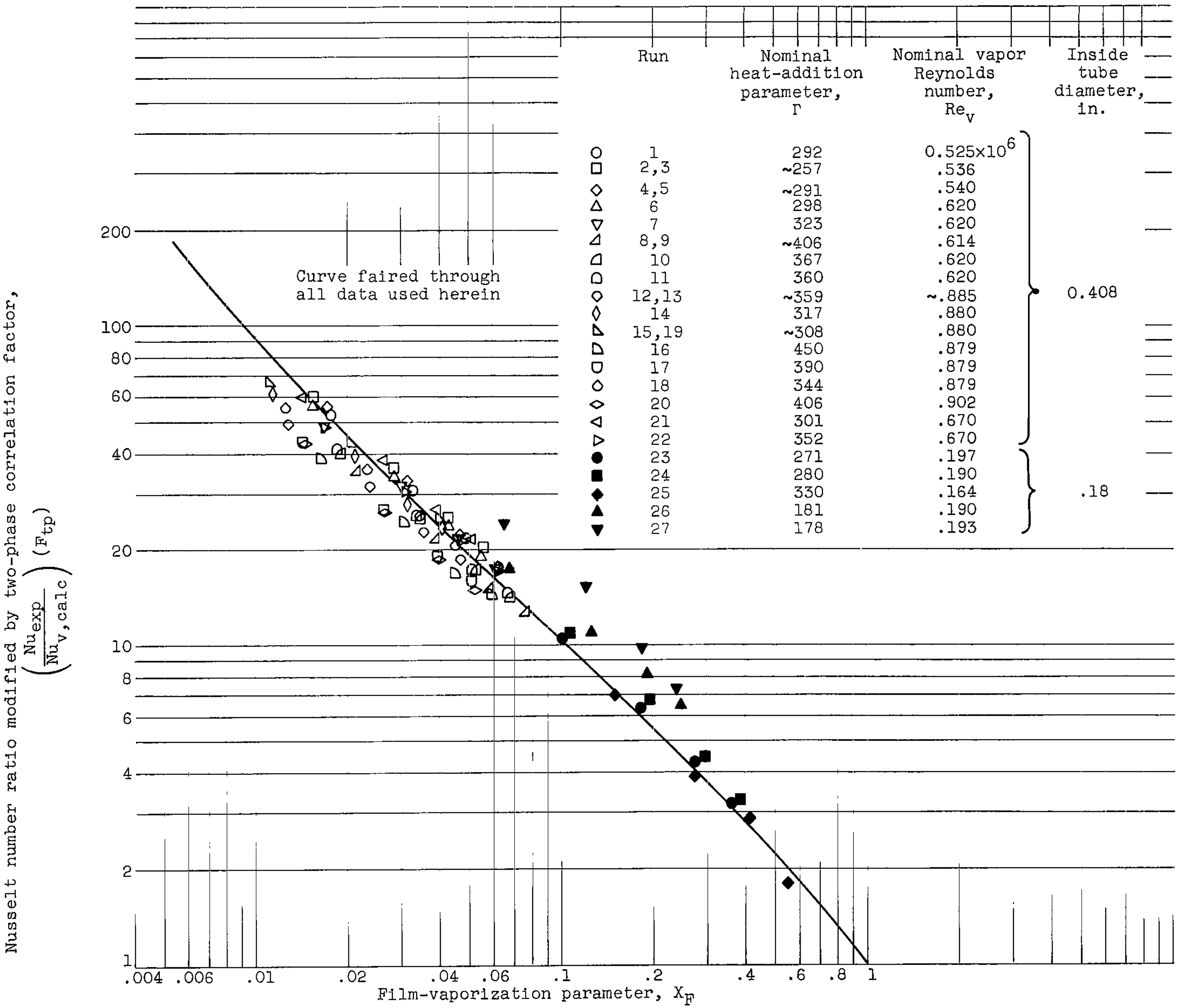
(f) 0.555-Inch inside diameter tube; $L_e/D > 3.5$; liquid nitrogen; reference 1.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



(g) 0.555-Inch inside diameter tube; $L_e/D > 3.5$; liquid hydrogen and nitrogen (single-point data runs); reference 1.

Figure 6. - Continued. Correlation of film-vaporization parameter with modified Nusselt number ratio.



(h) Freon 113; reference 4.

Figure 6. - Concluded. Correlation of film-vaporization parameter with modified Nusselt number ratio.

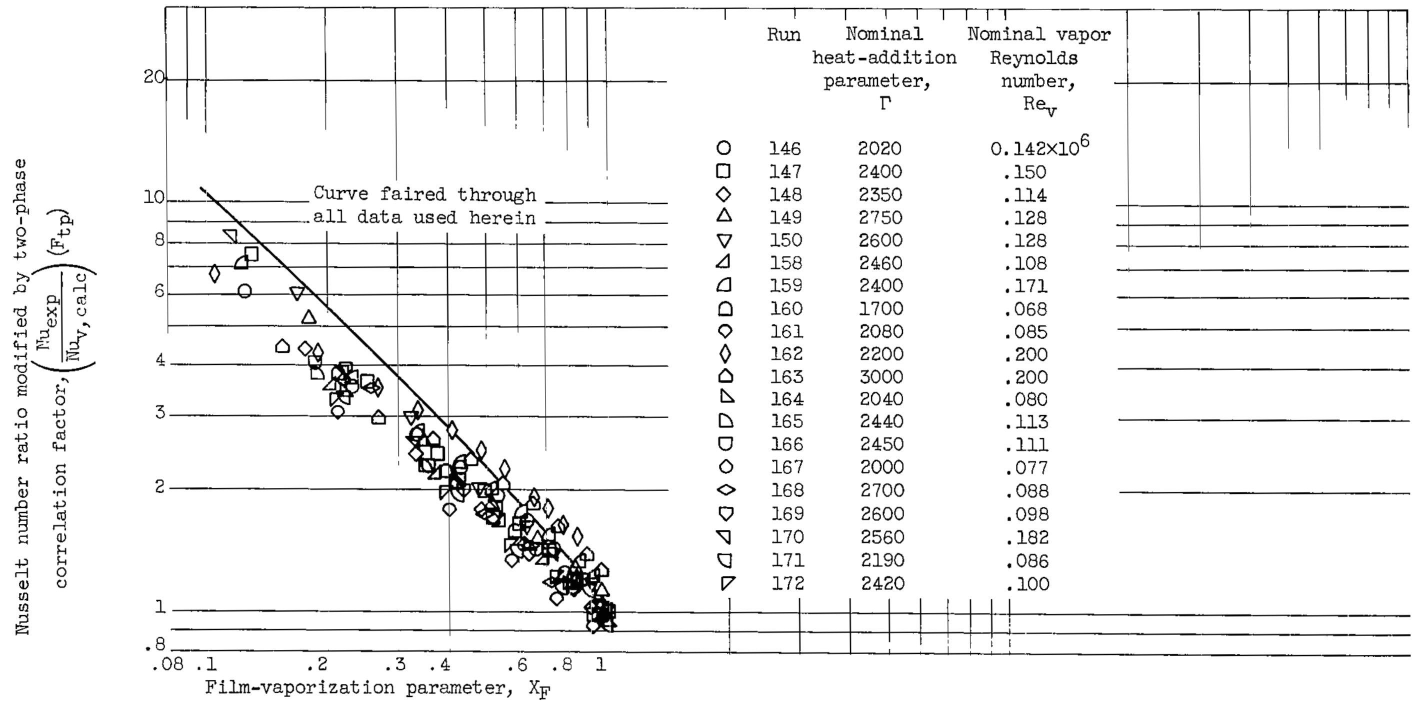


Figure 7. - Correlation of film-vaporization parameter with modified Nusselt number ratio. Liquid hydrogen; reference 1. ($L_e/D \cong 0.9$; exponent $a = 0.13$ in F_{tp} (eq. (8)).

2/7/87 Gr

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